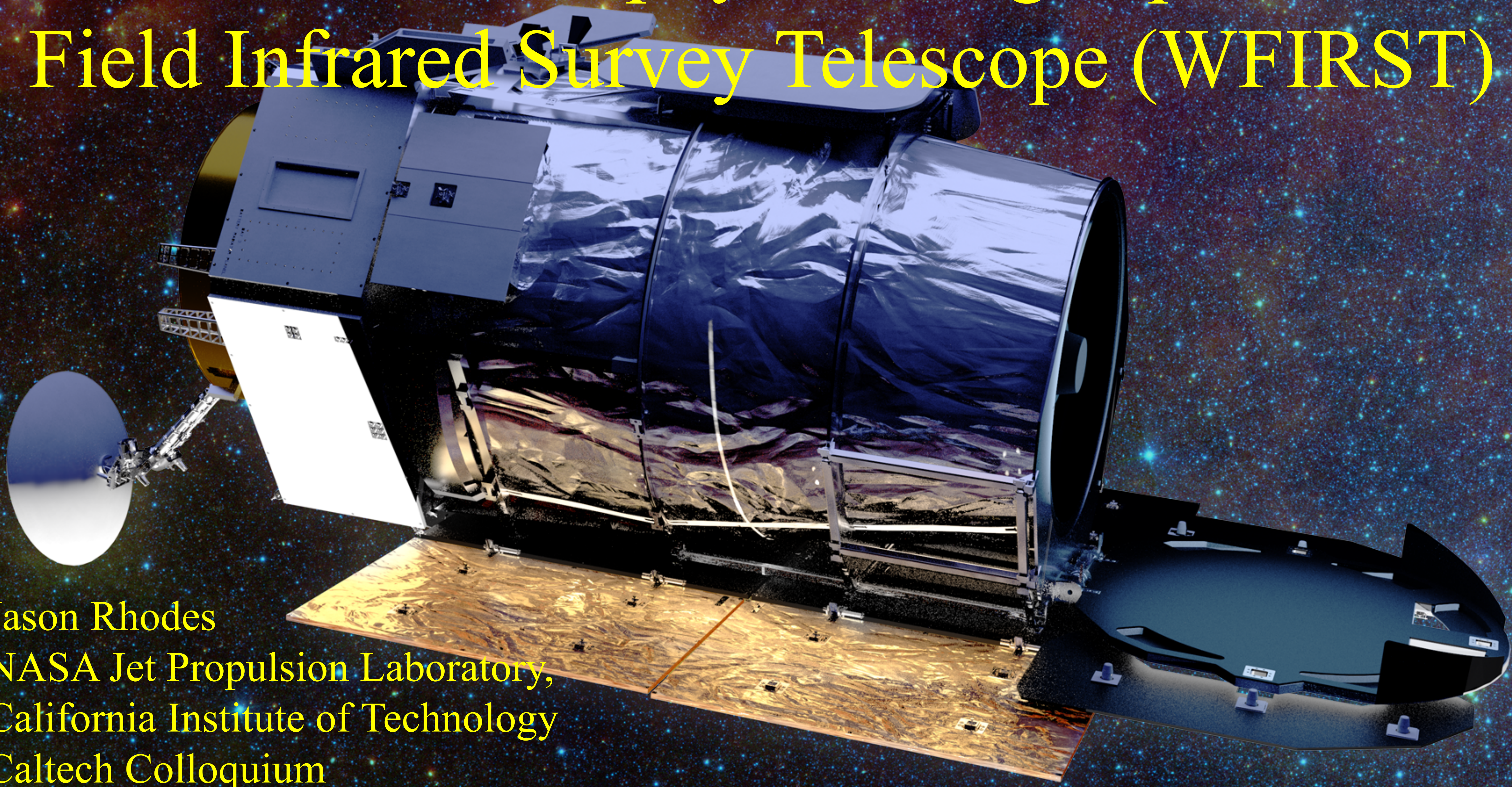
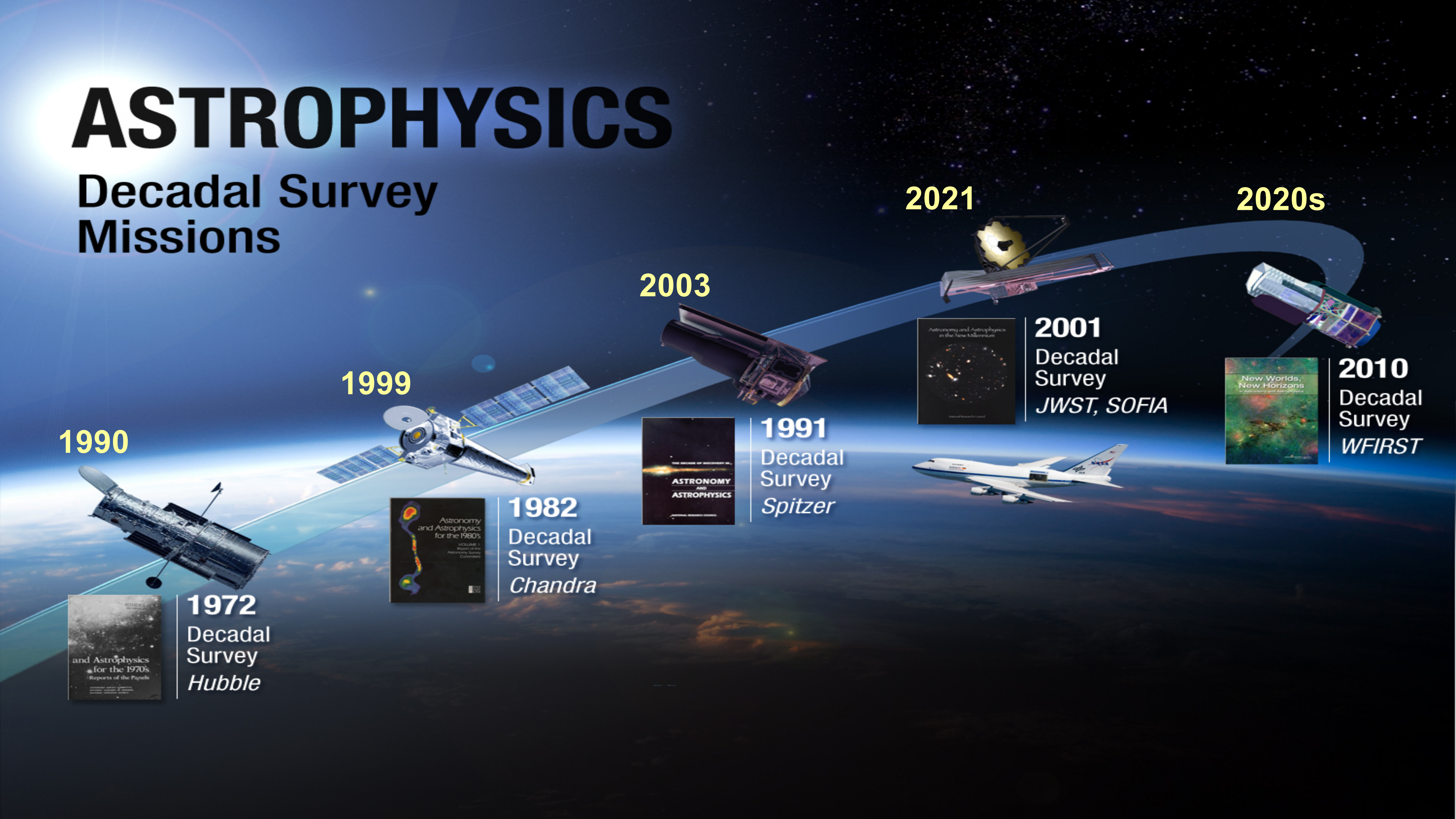
NASA's Next Astrophysics Flagship: The Wide Field Infrared Survey Telescope (WFIRST)



Jason Rhodes
NASA Jet Propulsion Laboratory,
California Institute of Technology
Caltech Colloquium
October 31, 2018

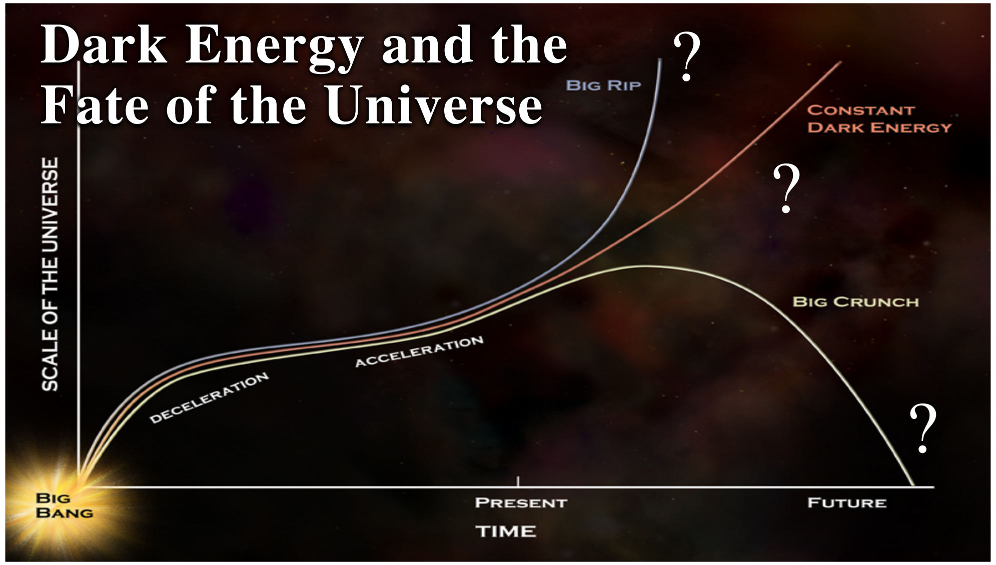
#NASAWFIRST

Jet Propulsion Laboratory
California Institute of Technology

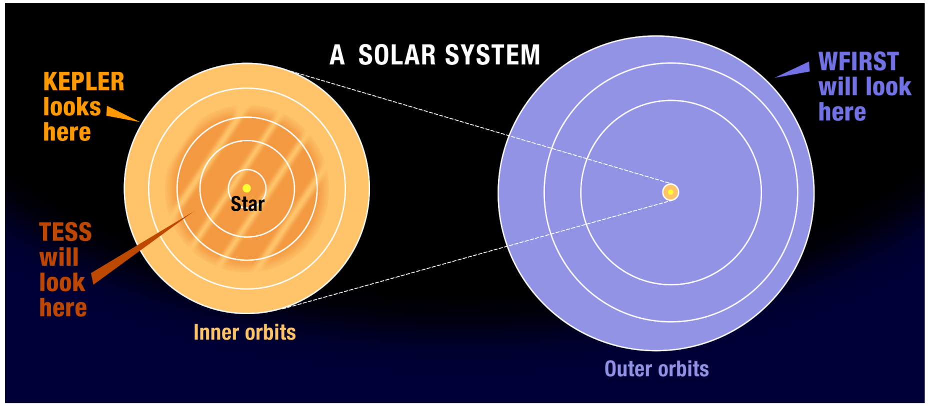

ASTROPHYSICS
Decadal Survey Missions
1990
1972 Decadal Survey
Hubble
and Astrophysics for the 1970's
Reports of the Panels
1999
1982 Decadal Survey
Chandra
Astronomy and Astrophysics for the 1980's
2003
1991 Decadal Survey
Spitzer
ASTRONOMY AND ASTROPHYSICS
2021
2001 Decadal Survey
JWST, SOFIA
Astronomy and Astrophysics in the New Millennium
2020s
2010 Decadal Survey
WFIRST
New Worlds, New Horizons

3/2018

Guidance from NWNH

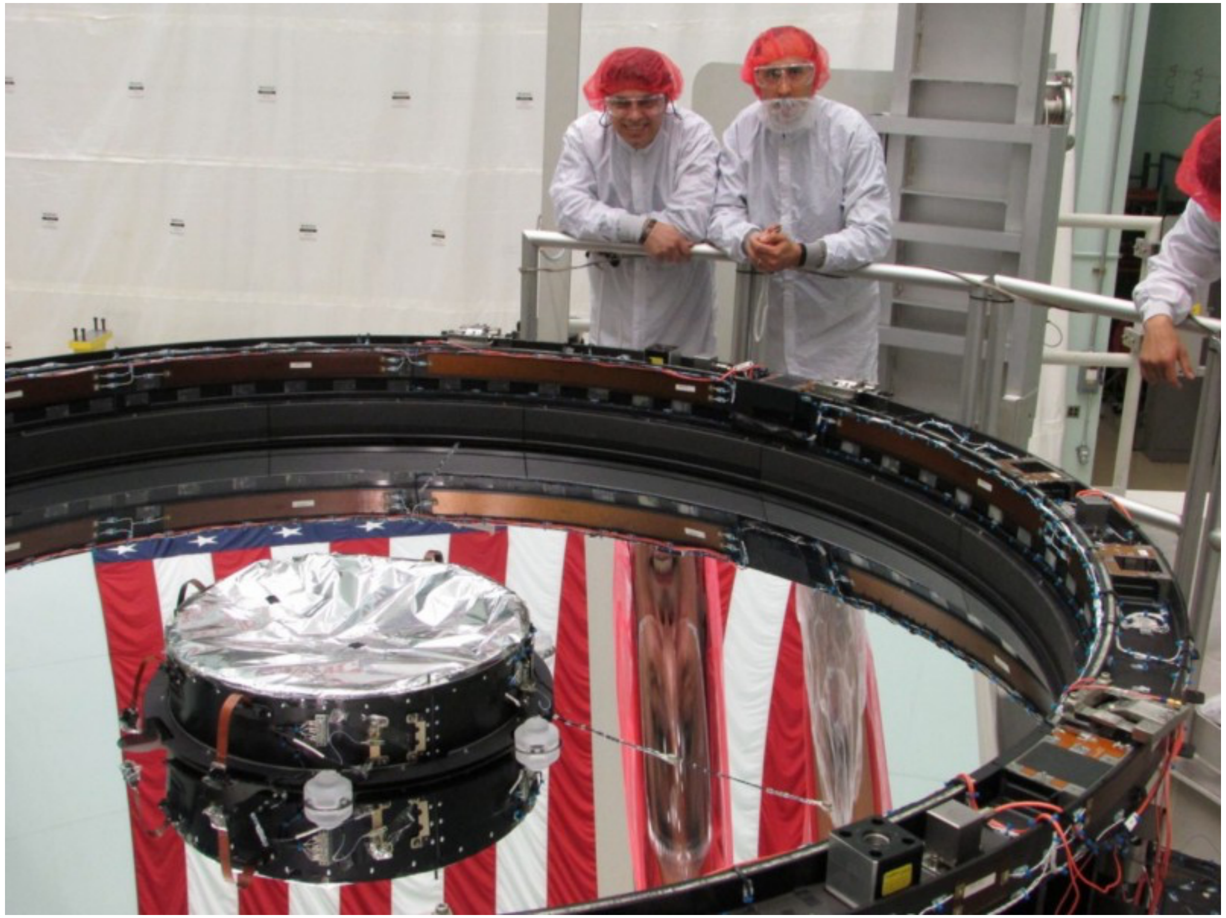


The full distribution of planets around stars



A Bigger WFIRST

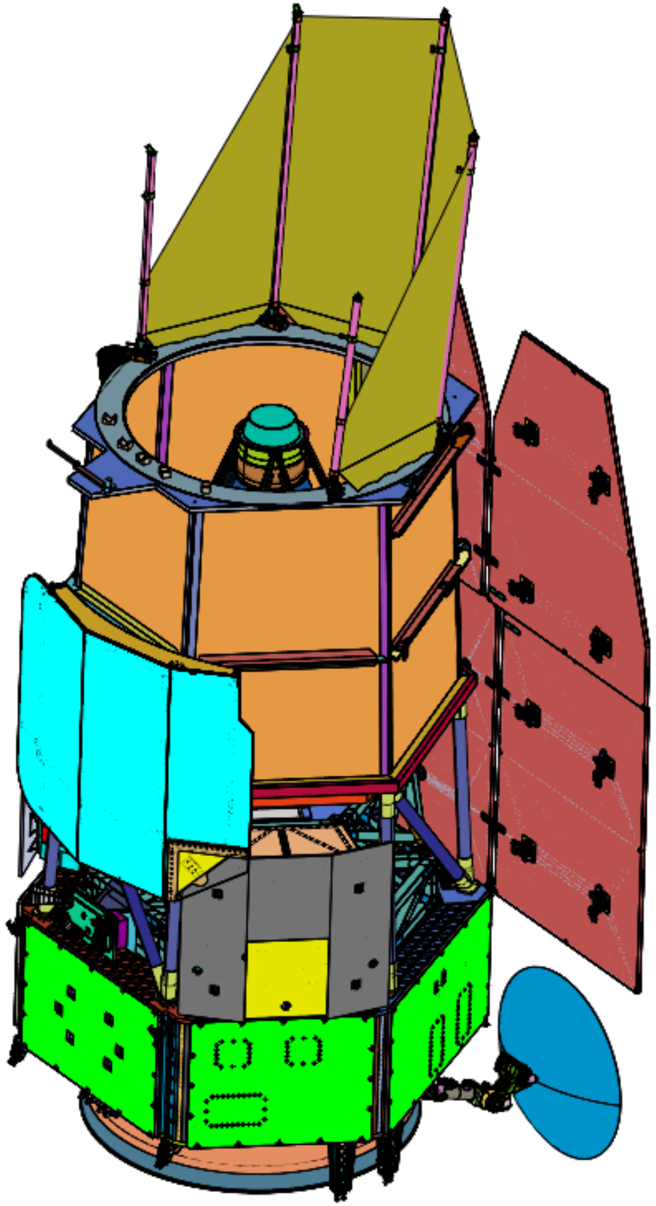
- Uses repurposed 2.4 m telescope from the another government agency
- Three science pillars: dark energy, exoplanets, infrared surveys
- Science done with Wide Field Instrument (WFI), with 18 H4RG detectors



Harris Corporation / TJT Photography

- Coronagraph Instrument (CGI) is a tech demo that will be ~1000x better than previous coronagraphs
- Designed to be Starshade ready
- Designed to be serviceable
- 5 year primary mission at L2
- 10+ year extended mission possible

WFIRST Observatory Concept



Key Features

Telescope: 2.4m aperture

Instruments:

- Wide Field Imager / Slitless Spectrometer
- Internal Coronagraph with Integral Field Spectrometer

Data Downlink: 275 Mbps

Data Volume: 11 Tb/day

Orbit: Sun-Earth L2

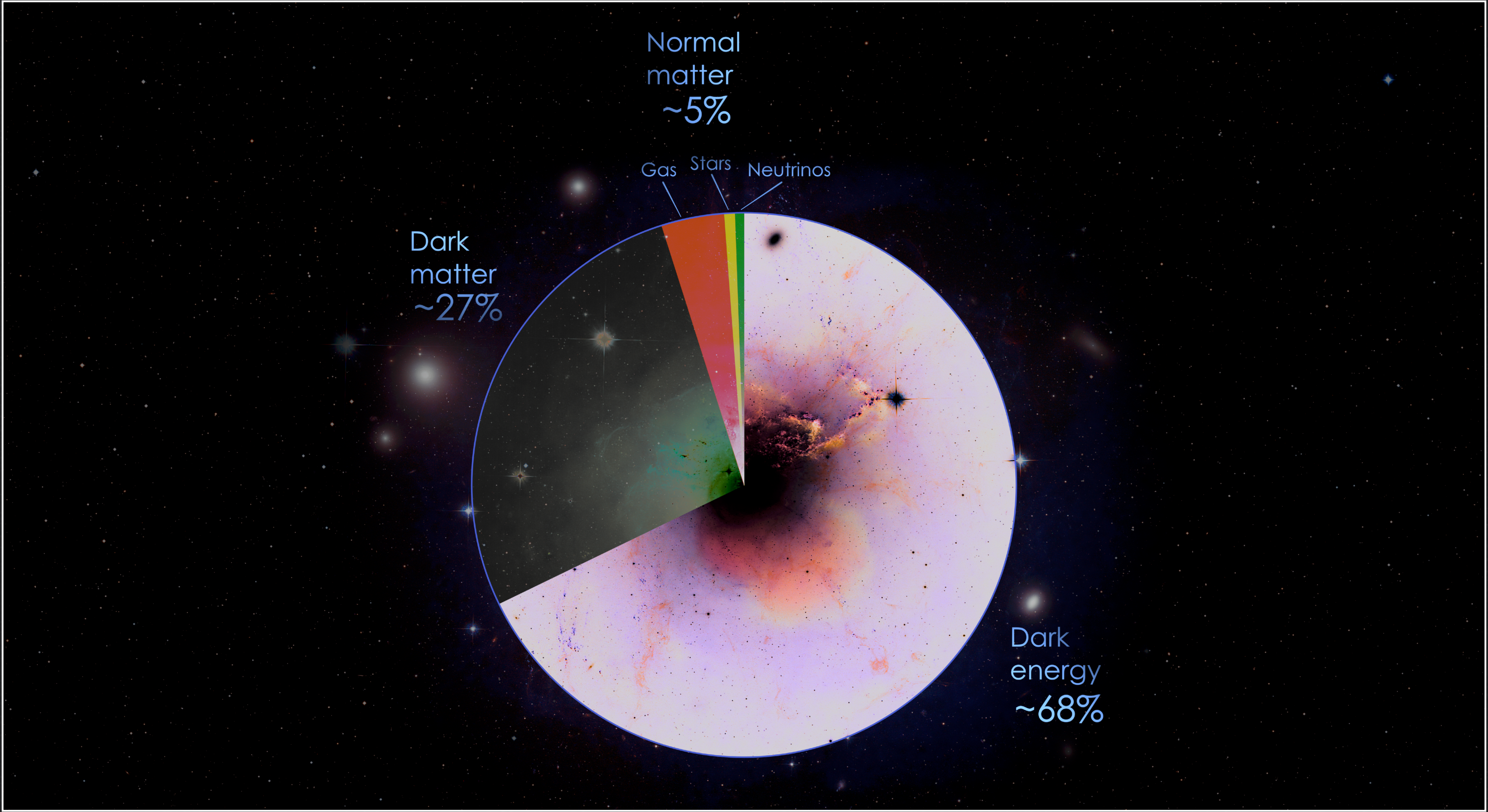
Launch Vehicle: 4 options

Mission Duration: 5 yr, 10yr goal

Serviceability: Observatory designed to be robotically serviceable

Starshade compatible

The Universe as a Pie Chart

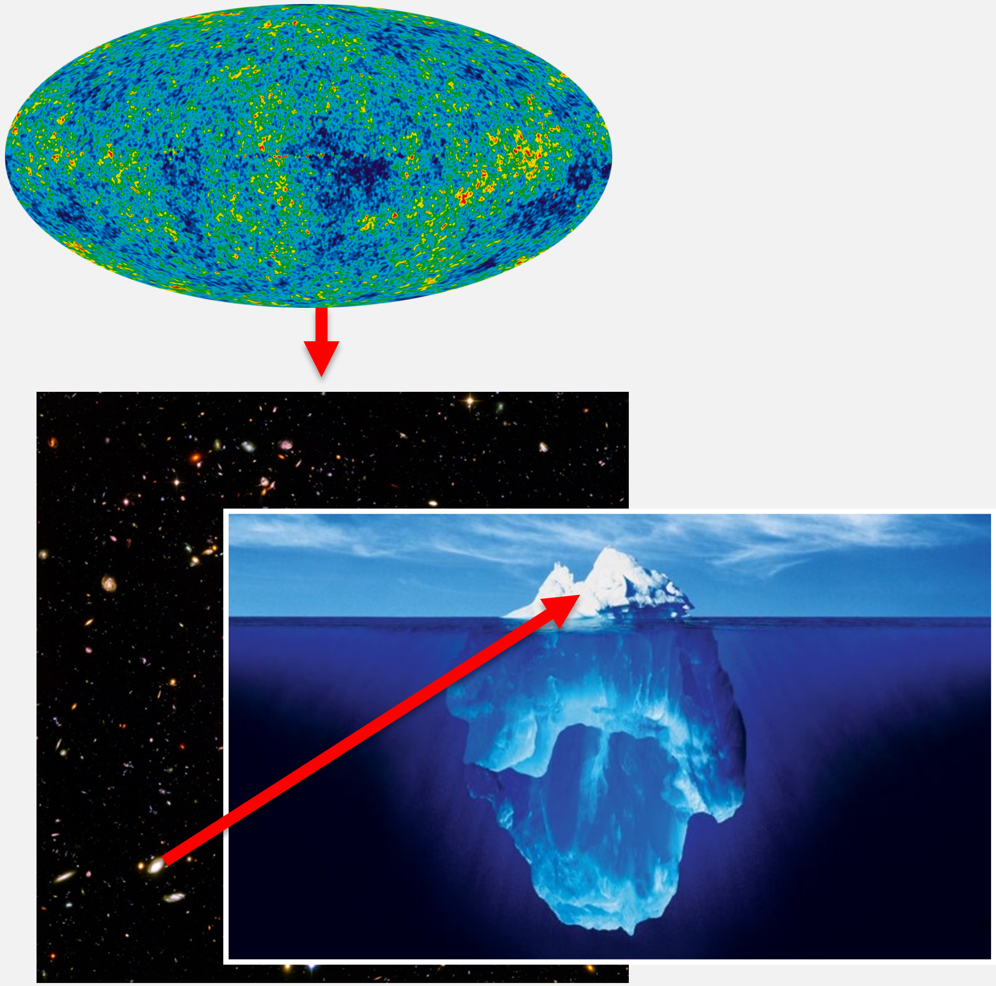


Consequences of DE

Dark Energy affects the:

- Expansion history of the Universe
  - How fast did the Universe expand?
  - Also called the geometry of the Universe

- Growth of structures
  - How do structures (which are mostly dark matter) evolve and grow over time
  - Attractive gravity competes with repulsive dark energy



If Einstein's General Relativity is wrong, modified gravity theories could explain the accelerating expansion.

This would change the above effects differently, *so we must measure them both!*

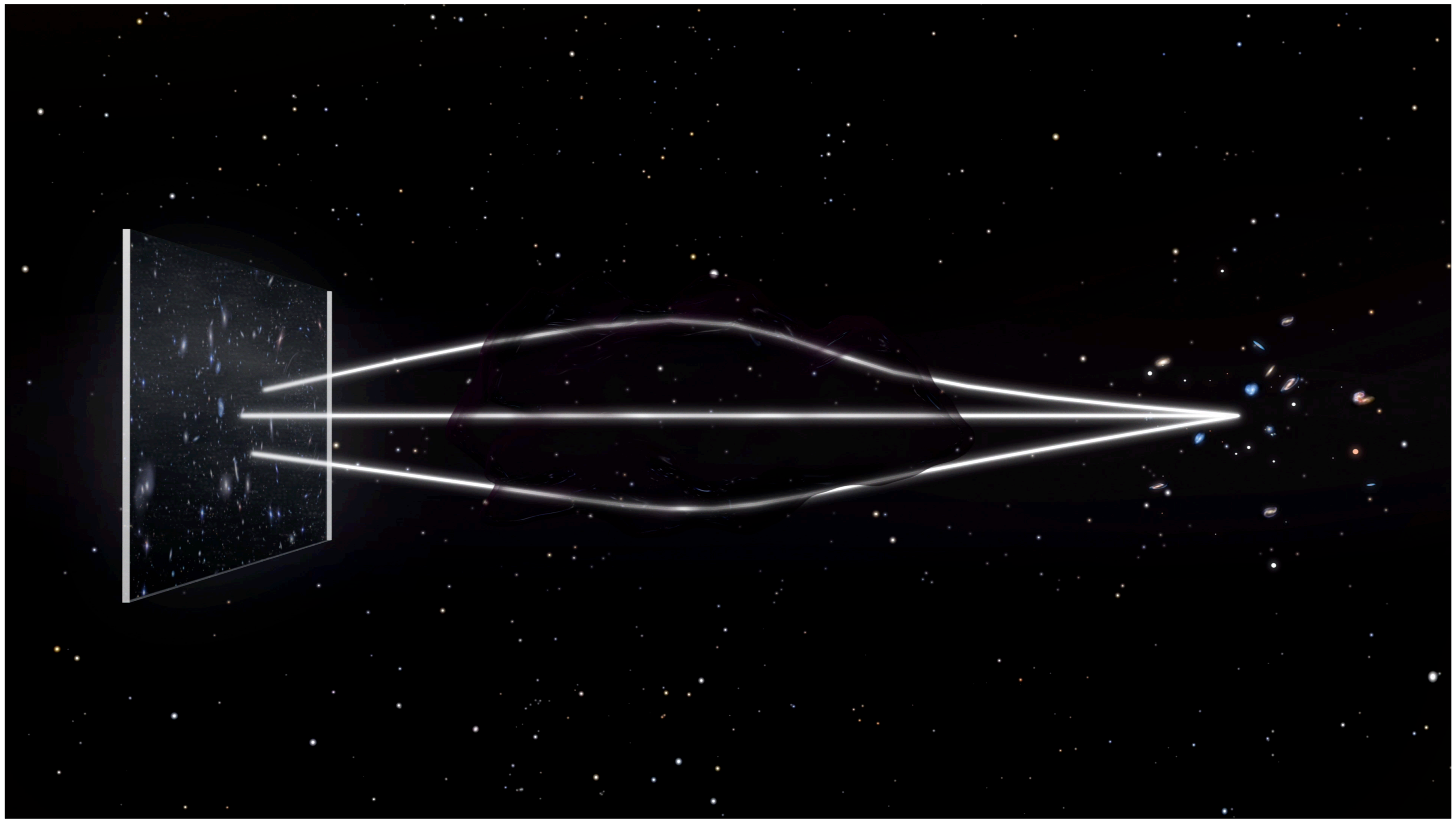
COSMOLOGY WITH THE HIGH LATITUDE SURVEY
SCIENCE INVESTIGATION TEAM

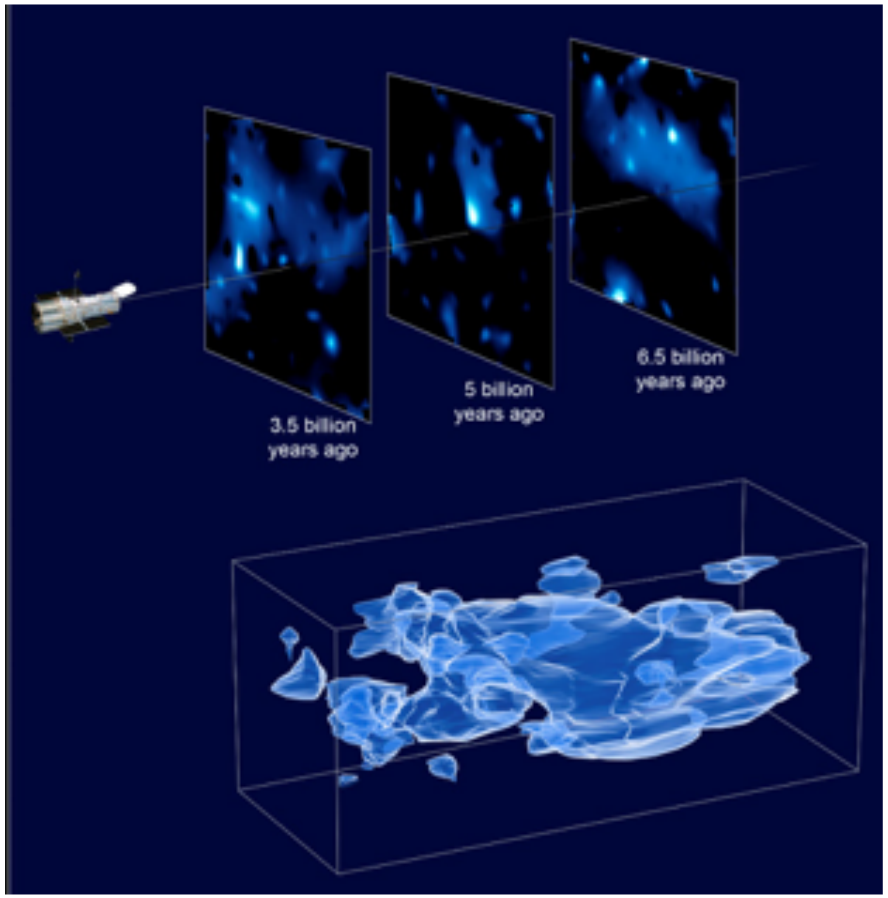
Olivier Doré (PI)	*JPL/Caltech*
Chris Hirata (WL lead)	*Ohio State U.*
Yun Wang (GRS lead)	*IPAC/Caltech*
David Weinberg (CL sub-lead)	*Ohio State U.*
Ivana Baronchelli	*IPAC/Caltech*
Rachel Bean	*Cornell*
Andrew Benson	*Carnegie*
Peter Capak	*IPAC/Caltech*
Ami Choi	*Ohio State U.U*
James Colbert	*IPAC/Caltech*
Tim Eifler	*JPL/U. Arizona*
Chen He Heinrich	*JPL*
Katrin Heitmann	*ANL*
George Helou	*IPAC/Caltech*
Shoubaneh Hemmati	*IPAC/Caltech*
Shirley Ho	*LBL/CCA*
Michael Hudson	*Waterloo*
Eric Huff	*JPL*
Albert Izard	*JPL*
Bhuvnesh Jain	*Penn*
Mike Jarvis	*Penn*
Alina Kiessling	*JPL*
Elisabeth Krause	*JPL/U. Arizona*

Alexis Leauthaud	*UCSC*
Robert Lupton	*Princeton*
Nial MacCrann	*Ohio State U.*
Rachel Mandelbaum	*CMU*
Elena Massara	*UCB*
Dan Masters	*JPL*
Alex Merson	*JPL*
Hironao Miyatake	*JPL*
Nikhil Padmanabhan	*Yale*
Alice Pisani	*Princeton*
Andres Plazas Malagon	*JPL*
Eduardo Rozo	*U. Arizona*
Lado Samushia	*U. Kansas*
Mike Seiffert	*JPL*
Charles Shapiro	*JPL*
Melanie Simet	*JPL*
Kendrick Smith	*Perimeter Institute*
David Spergel	*Princeton/CCA*
Masahiro Takada	*Kavli IPMU Tokyo*
Harry Teplitz	*IPAC*
Michael Troxel	*Ohio State U.*
Anja von der Linden	*Brookhaven*
Hao-Yi Wu	*Ohio State U.*
Ying Zu	*Ohio State U.*

WFIRST will

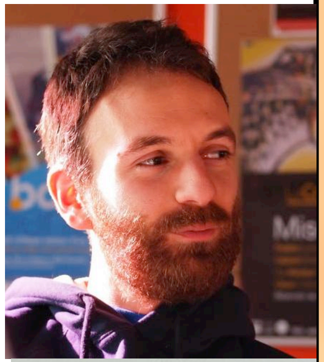
measure galaxy shapes to map dark matter and measure the growth of galaxies over the Universe's life



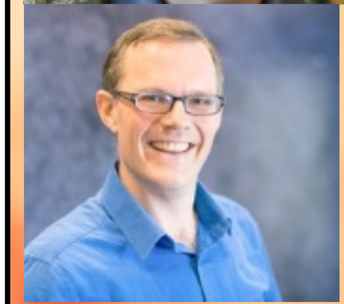


From Massey, Rhodes, et al 2007

C3R2 = Complete Calibration of the Color-Redshift Relation





Judith Cohen (Caltech) - PI of Caltech Keck C3R2 allocation
16 nights (DEIMOS + LRIS + MOSFIRE, kicked off program in 2016A)
Daniel Stern (JPL) - PI of NASA Keck C3R2 allocation
10 nights (all DEIMOS; “Key Strategic Mission Support”)
Daniel Masters (JPL) – PI of NASA Keck C3R2 allocation 2018A/B
10 nights (5 each LRIS/MOSFIRE; “Key Strategic Mission Support”)
Dave Sanders (IfA) - PI of Univ. of Hawaii Keck C3R2 allocation
6 nights (all DEIMOS) + H20
Bahram Mobasher (UC-Riverside) - PI of UC Keck C3R2 allocation
2.5 nights (all DEIMOS)

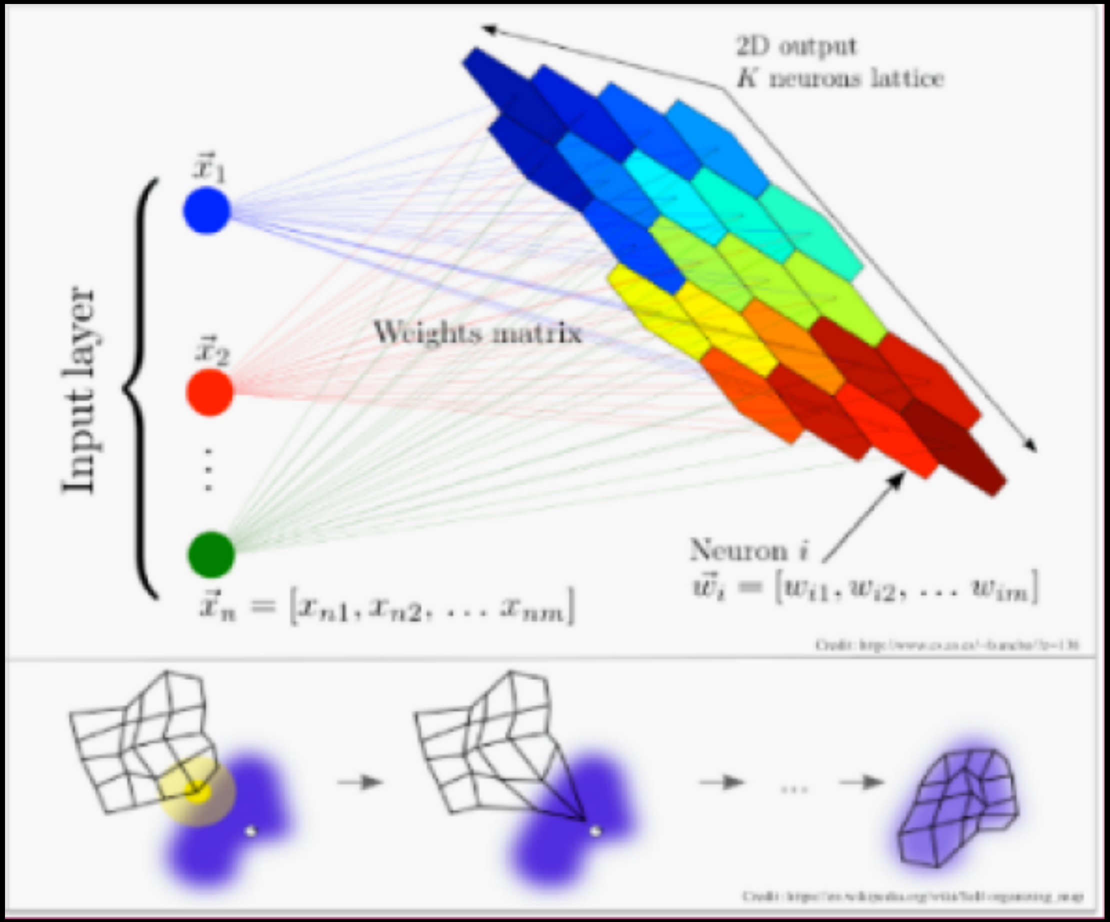
+ time allocations on VLT (PI F. Castander), MMT (PI D. Eisenstein), and GTC (PI C. Guitierrez)
-Sample drawn from 6 fields totaling ~6 deg^2

Additional Collaborators: Peter Capak, S. Adam Stanford, Nina Hernitschek, Francisco Castander, Sotiria Fotopoulou, Audrey Galametz, Iary Davidzon, Stephane Paltani, Jason Rhodes, Alessandro Rettura, Istvan Szapudi, and the Euclid Organization Unit – Photometric Redshifts (OU-PHZ) team

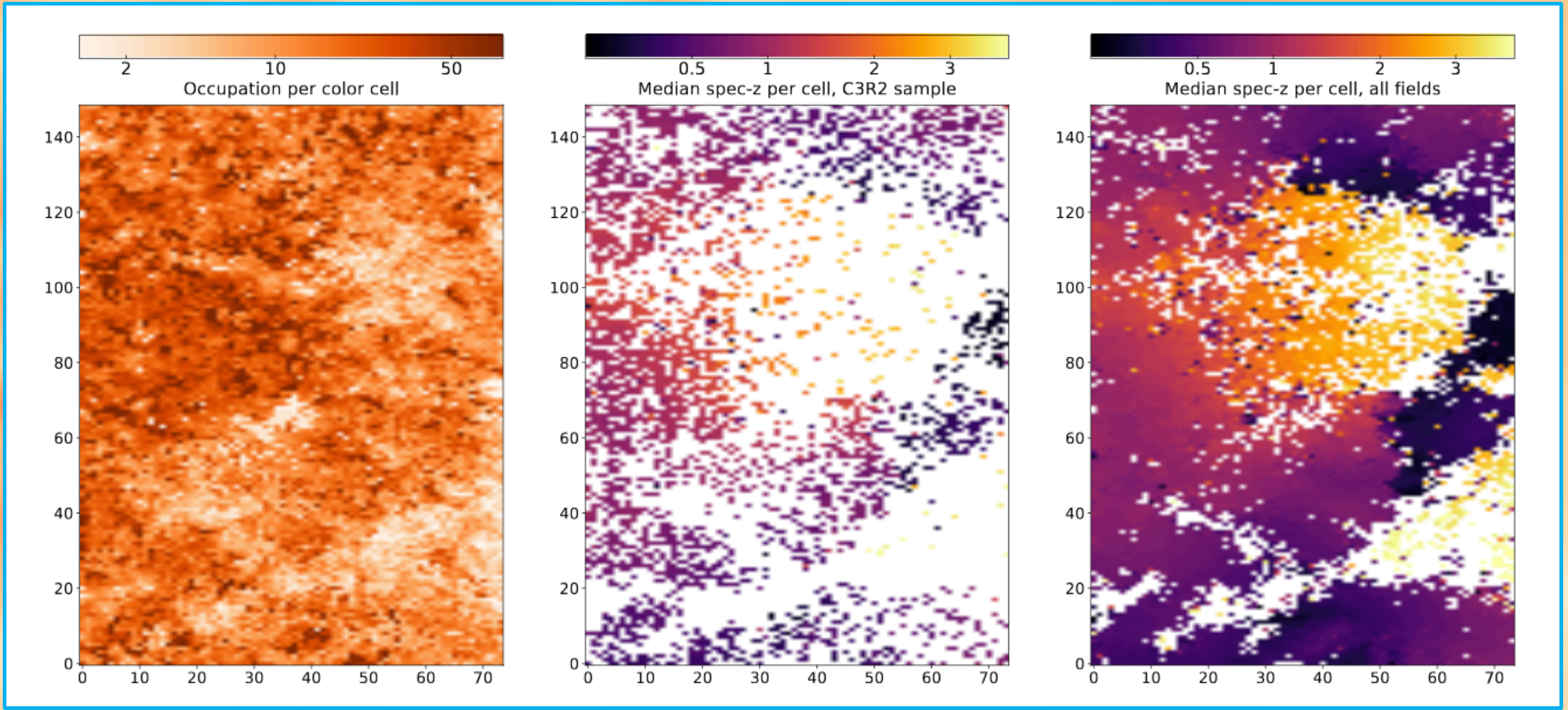
Self Organizing Maps

Class of Unsupervised Neural Networks which reduce multi-dimensional space to two dimensions while preserving the topology. SOMs offer:

1. An empirical model-independent relation between colors (galaxy SED shape) and redshift.
2. Visualizing galaxy parameter space
3. Spectroscopic target selection from the voids in previous surveys
4. Calibration of photometric redshifts in each SOM cell with minimum number of spectra acquired.
5. Selection of tomographic bins from a group of SOM cells

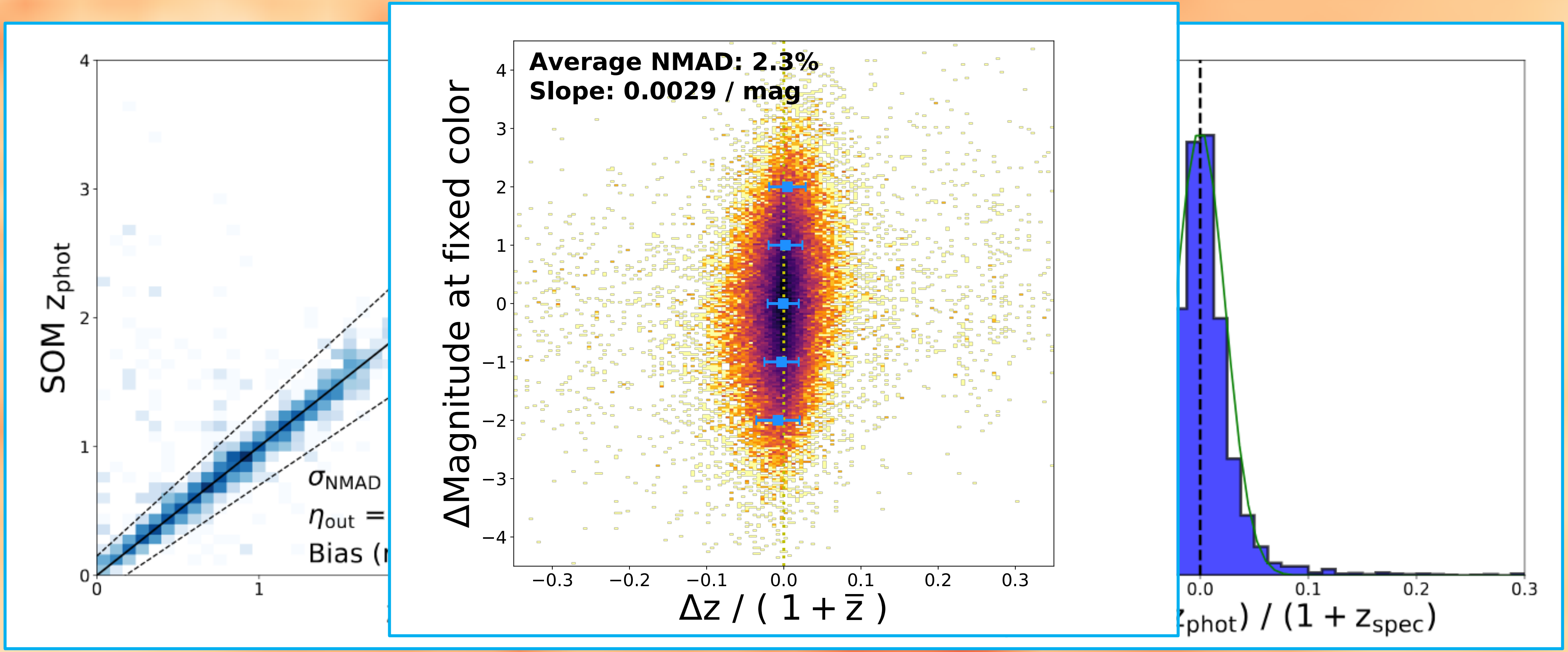


Color coverage to Euclid depth



- Much of the galaxy color space explored to significant depth (>75% of cells; >85% of galaxies in cell with at least 1 specz, many cells with >>1 specz); some cells remain uncalibrated at present
- Uncalibrated cells correspond to less common sources
- C3R2-Keck alone covers >35% of the color space, mostly disjoint from what was previously explored

C3R2 – Results from SOM method



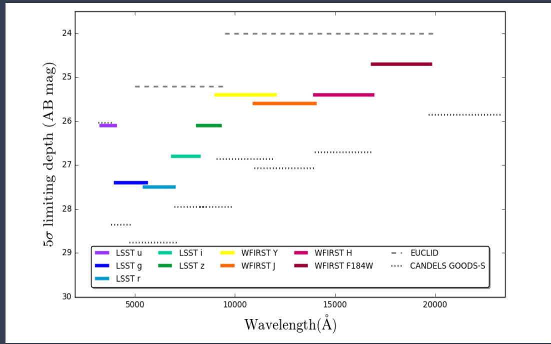
- Compare spec-zs of unique pairs of galaxies at fixed color (SOM position)
- Illustrates weak (and measurable) secondary dependence of redshift on magnitude *at fixed color* in the LSST+Euclid color space

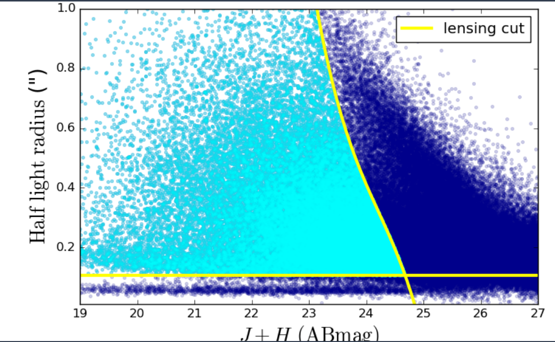
Outlier fraction 4.1%, scatter 2.3%, bias of -0.2%

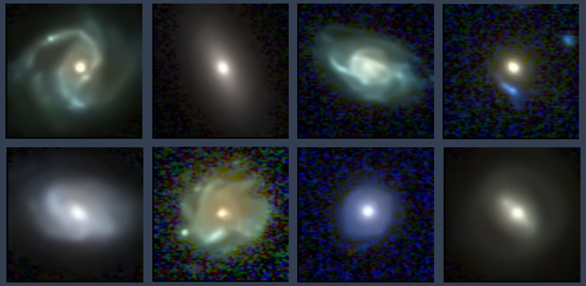
→ Method achieving unbiased performance

WFIRST Weak Lensing Photometric Redshift Calibration (Hemmati et al. 2018)

Synthetic LSST+WFIRST catalog: based on deep five field CANDELS observations, and a cut on size and S/N to select galaxies suitable for weak lensing measurements.





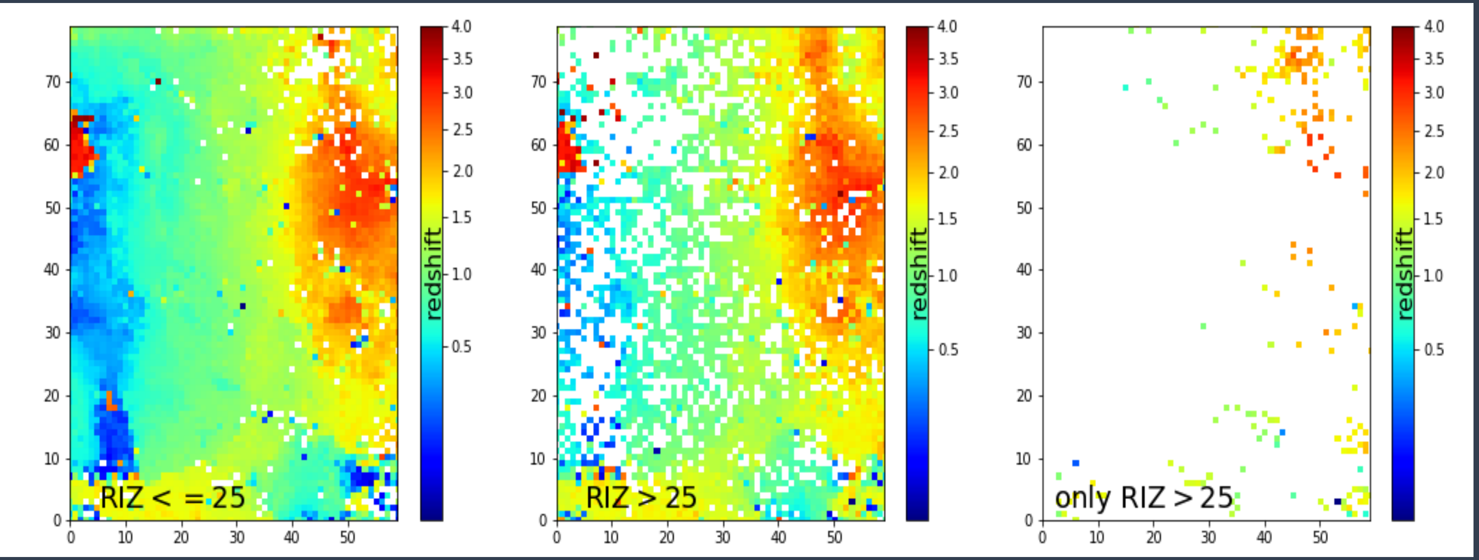


LSST+ WFIRST SOM trained with colors, color-coded with median photo-z of galaxies in each cell. 57% of the cells contain high confidence spec-z in the CANDELS fields (MOSDEF, CANDELS, etc.) → ~2.5k high quality spectra needed to fill the SOM with at least one spectra per cell.

WFIRST can use Euclid calibration of brighter galaxies (C3R2 - Masters et al.)

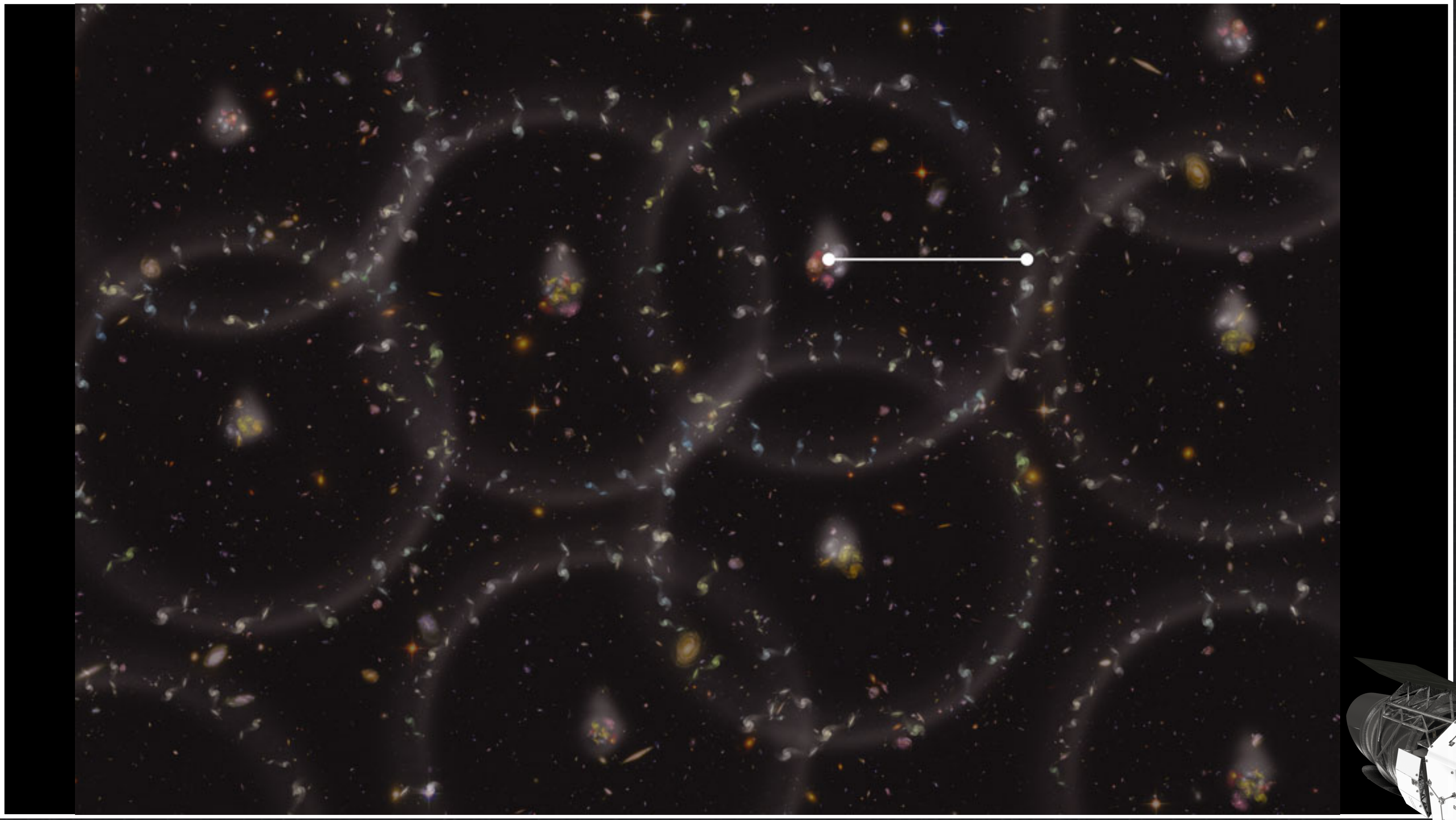
- 26% of WFIRST sample is fainter than Euclid.
- 91% of WFIRST galaxies live in cells with a bright source.
- 4% of the SOM cells have no bright galaxy counterpart.

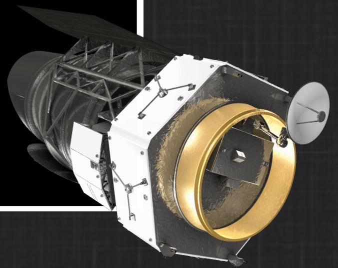
Minimum spectroscopy recommended for WFIRST ~0.5-1.2k



WFIRST will

map the positions of galaxies to establish a cosmic standard ruler to measure the Universe’s expansion history





#WFIRST

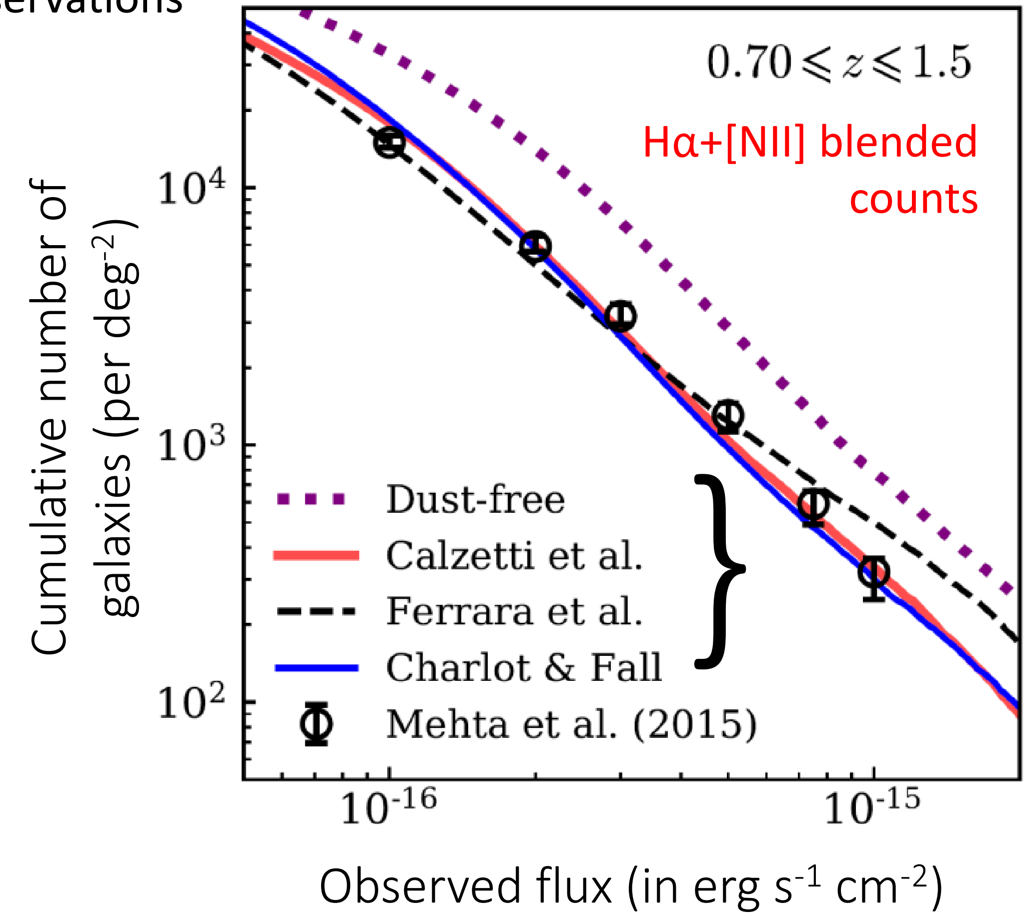
How many Hα-emitting galaxies do we expect to observe?

- **Accurate forecasts of number density of Hα-emitting (star-forming) galaxies allows us to optimize survey strategy so can maximize figure-of-merit**.
- Large scatter in previous forecasts due to limited size of existing observations (small area on sky).

Objective: Use a physically-motivated galaxy formation model to make robust predictions for the number density of Hα-emitting galaxies that we expect to see with WFIRST.

- Built galaxy mock catalog using **Galacticus** – an open source semi-analytical model (Benson 2010).
- **Able to match counts from the WFC3 Infrared Spectroscopic Parallels (WISP) Survey (Mehta et al.).**
  - Consider three different dust models (Ferrara et al. 1999, Calzetti et al. 2000, Charlot & Fall 2000).

Merson et al. (2018), MNRAS, 474, 177-196

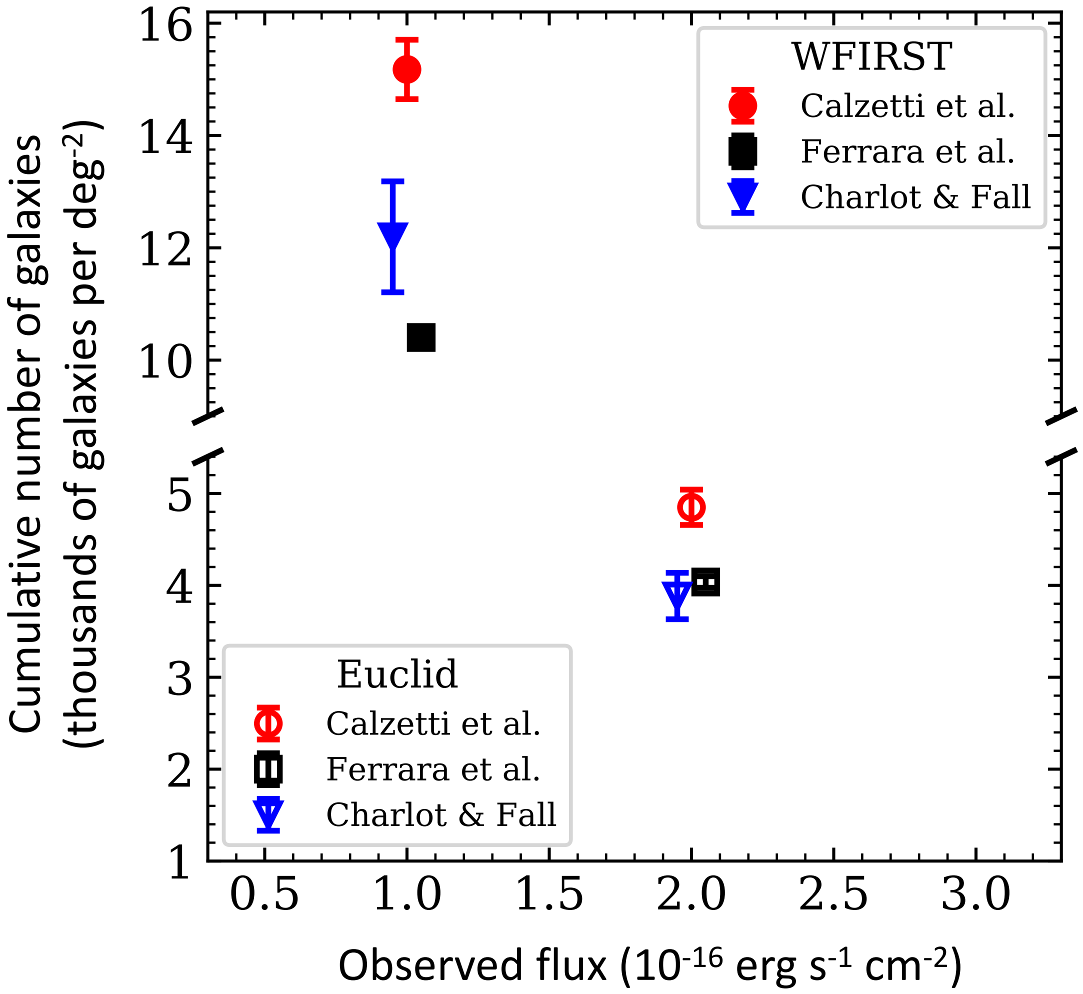


How many Hα-emitting galaxies do we expect to observe?

Counts for WFIRST-like survey (1<z<2)

Flux Limit	Ferrara et al. (1999)	Calzetti et al. (2000)	Charlot & Fall (2000)
> 1×10^{-16} erg/s/cm^{-2}	10,403 ± 138 (deg^{-2})	15,176 ± 528 (deg^{-2})	12,195 ± 987 (deg^{-2})

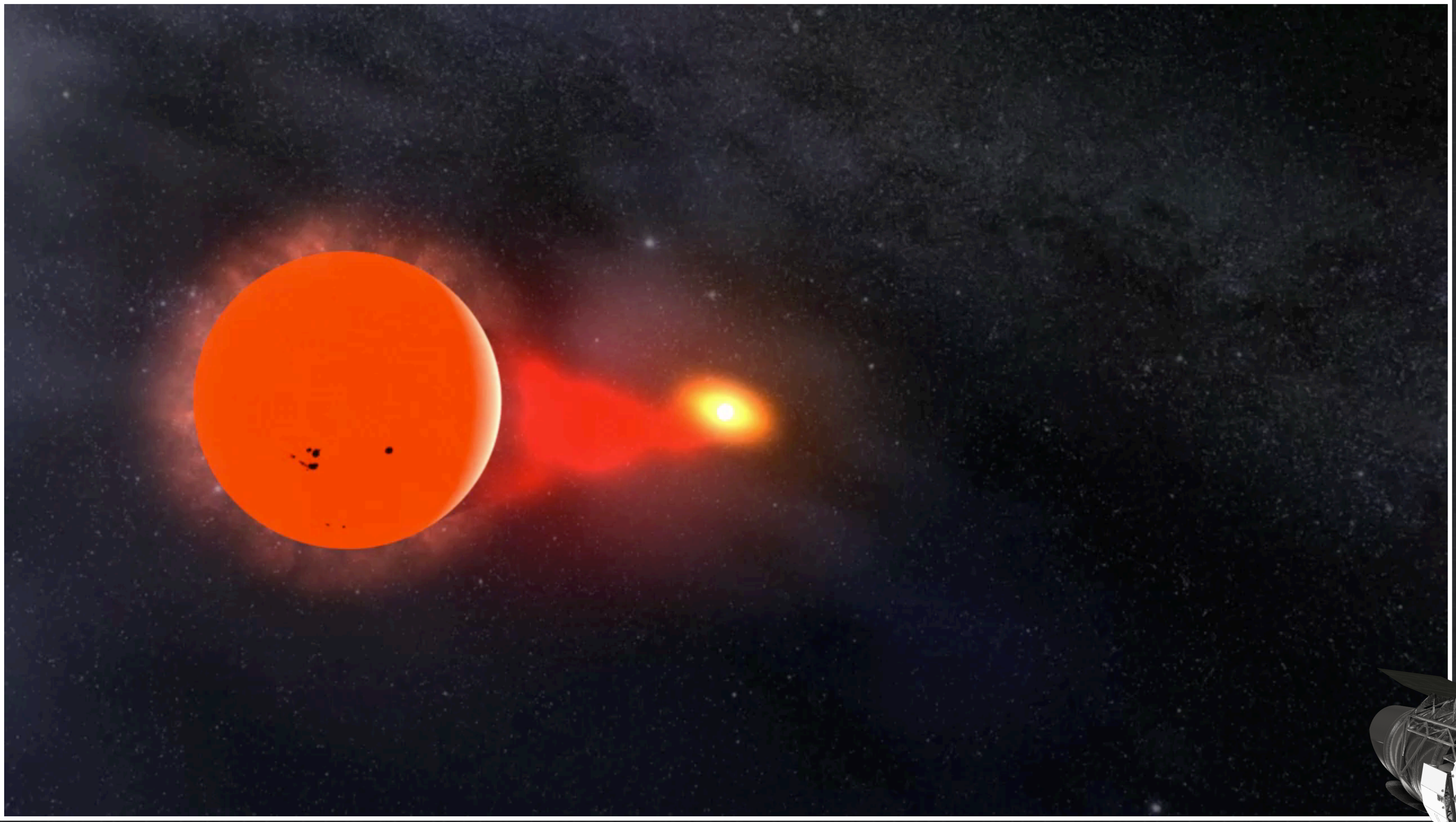
- Scatter of 20-50% in counts between different dust models – this **scatter is comparable or smaller than previous forecasts.**
- **Robust predictions**: physically-motivated galaxy formation model with properties calculated self-consistently.
- Counts suggest that **WFIRST will be able to observe number of galaxies to meet scientific requirements**.

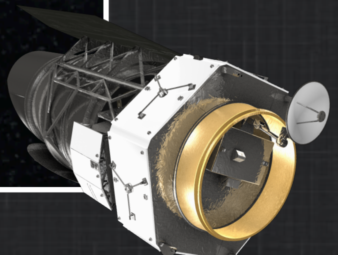


Merson et al. (2018), MNRAS, 474, 177-196

WFIRST will

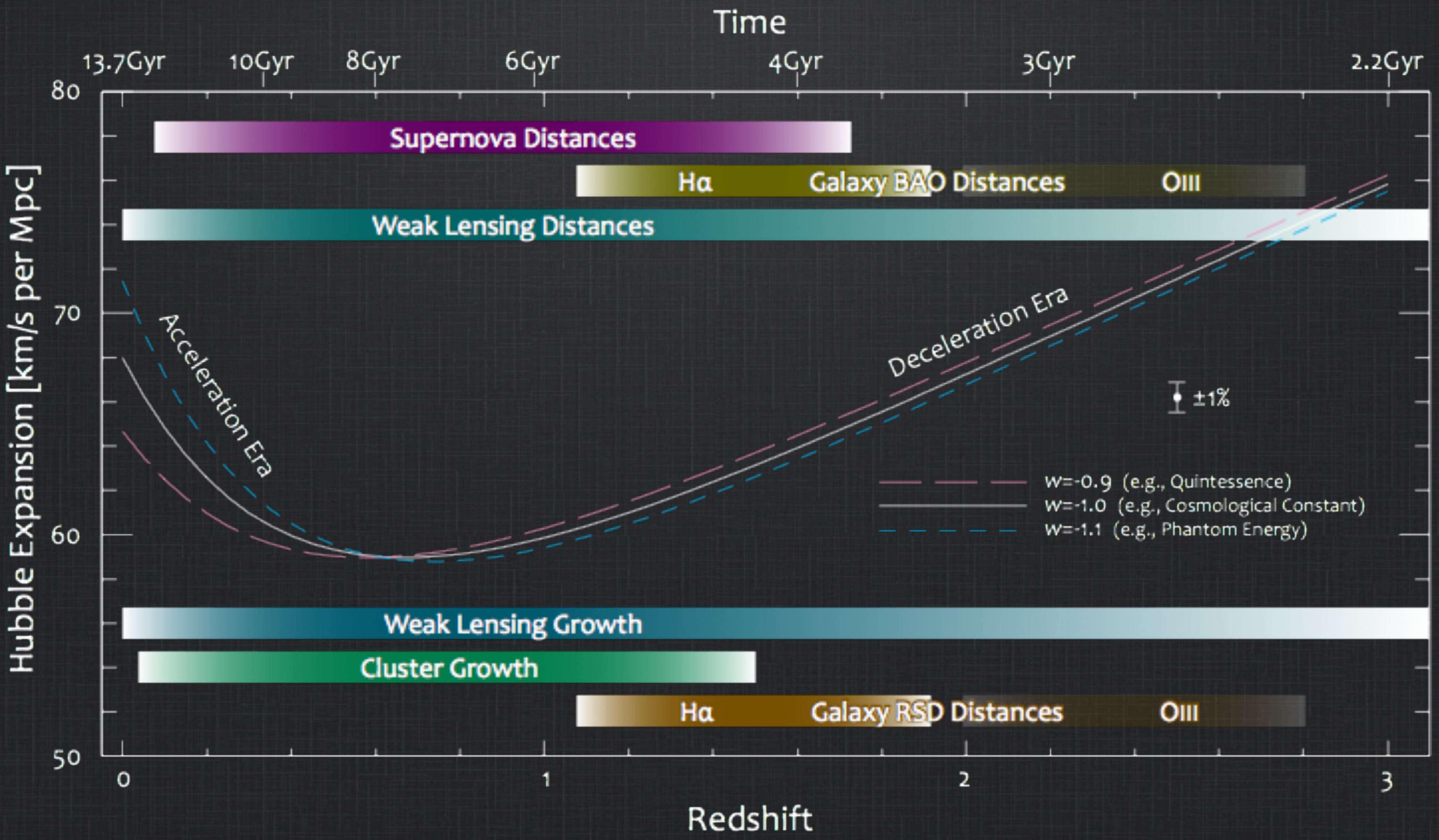
discover exploding stars (supernovae) across cosmic time to establish precise distances to galaxies





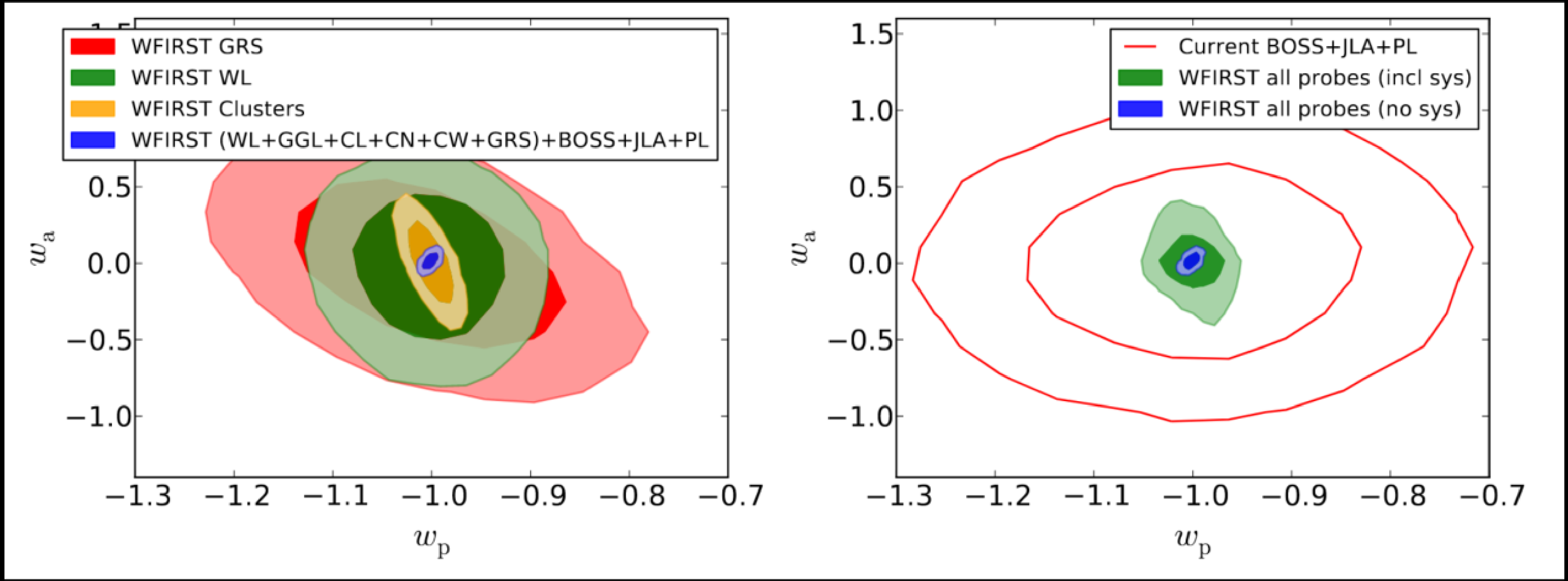
#WFIRST

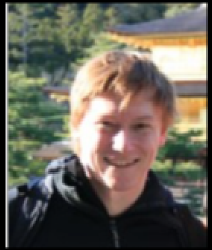
WFIRST Probes of Expansion and Growth



WFIRST: A MULTI-PROBE MISSION





Eifler, Heinrich, Krause, Miyatake, Simet et al., 2018, *in prep*.

NExScI

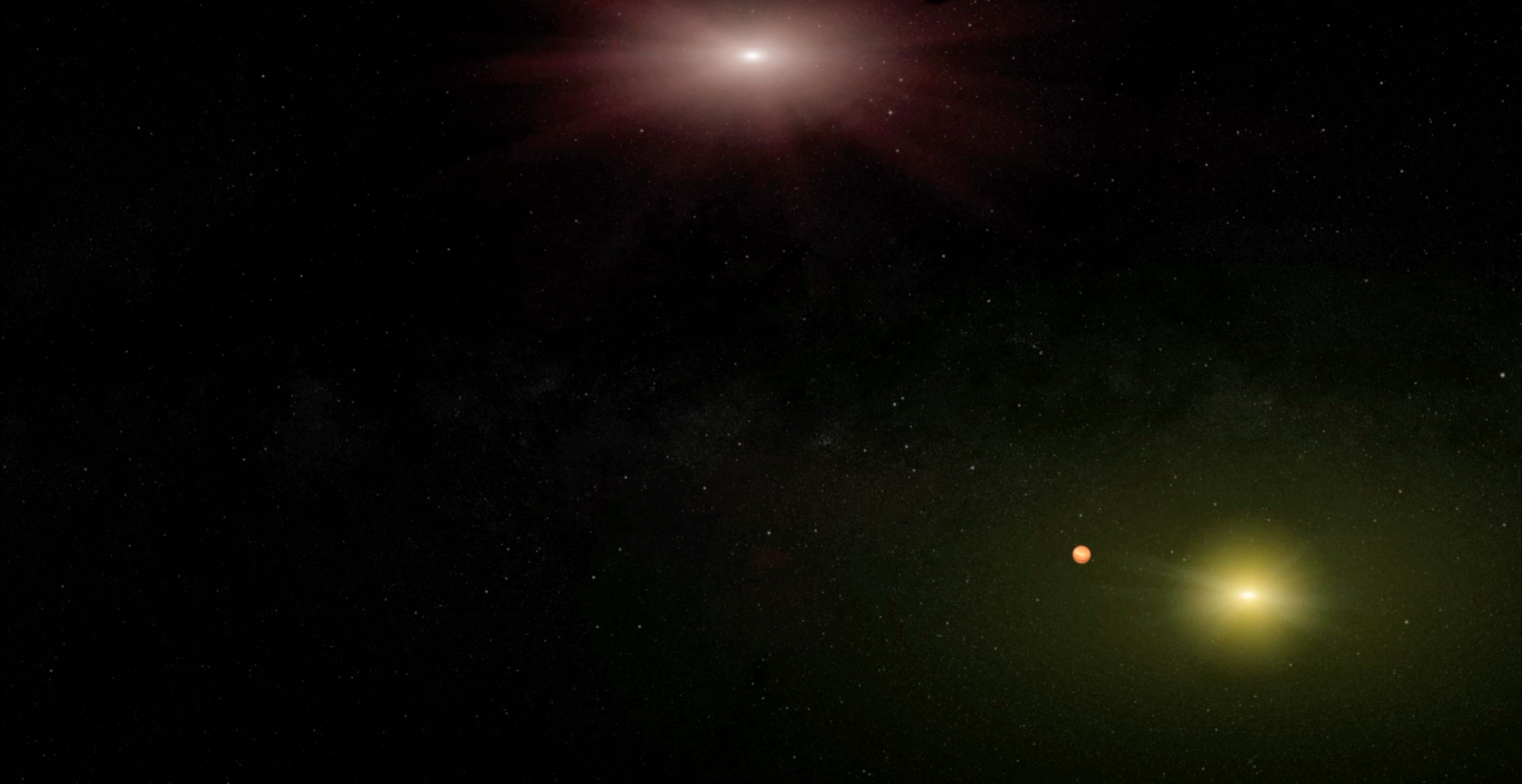
ipac

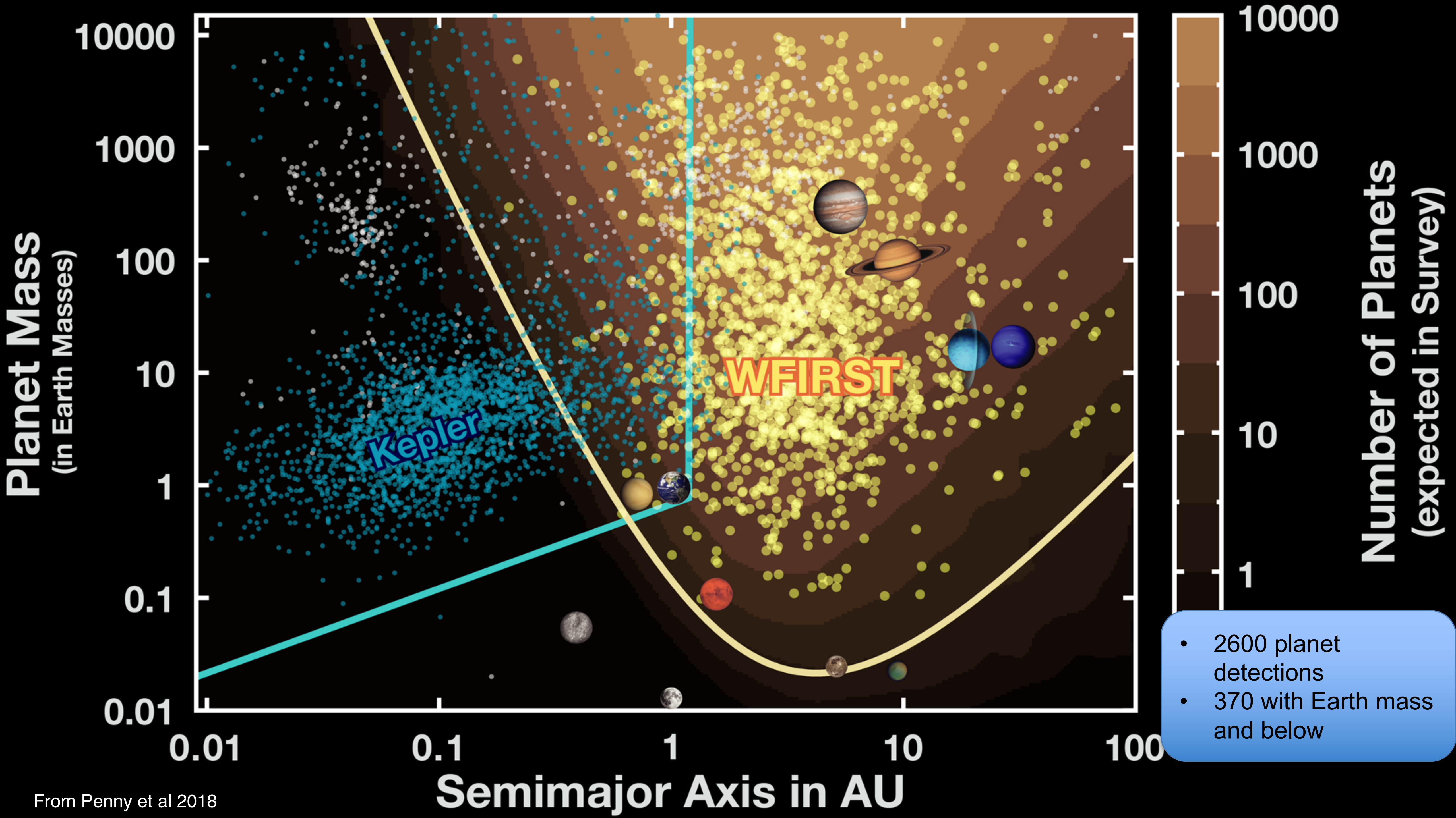
Exoplanets: Detections by Discovery Year

1989-2018

Plots generated Sept. 27, 2018

Microlensing



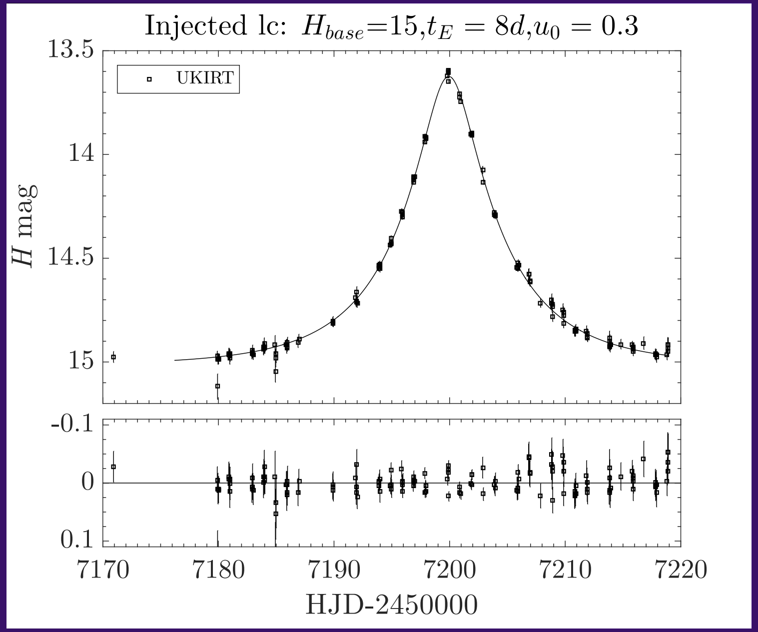


- 2600 planet detections
- 370 with Earth mass and below

From Penny et al 2018

UKIRT Microlensing Survey to Identify WFIRST Target Fields

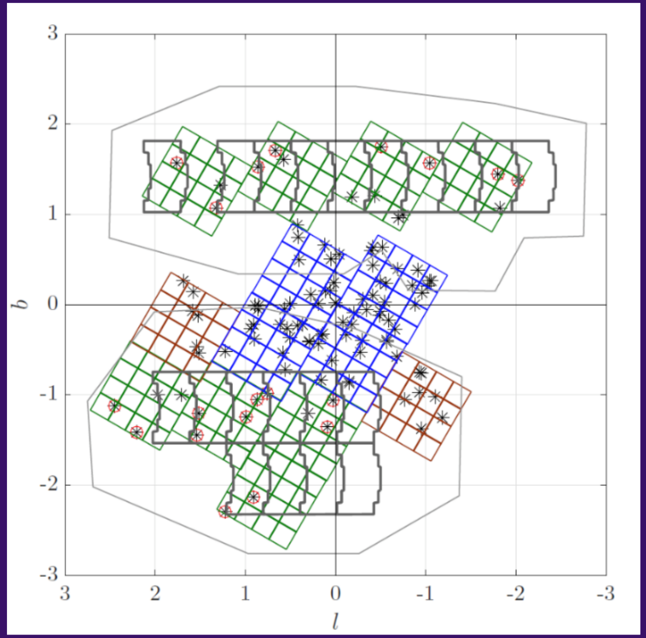
Injected Microlensing Events



Jacklin et al. *in prep*

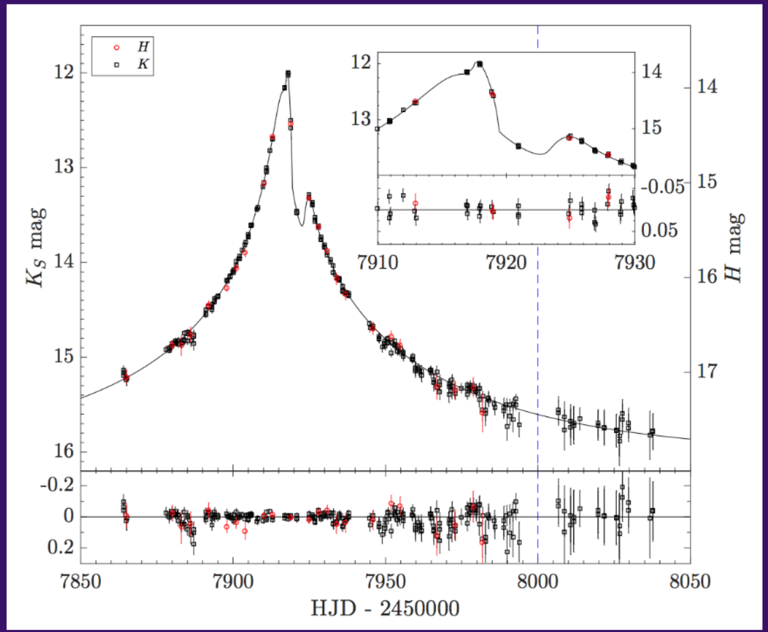
+

Total UKIRT Microlensing Events



Shvartzvald et al. *in prep*

UKIRT Planetary Events



Shvartzvald et al. 2018

UKIRT Detection Efficiency & Event Rate in Proposed WFIRST Fields

UKIRT-only Planet Discovery

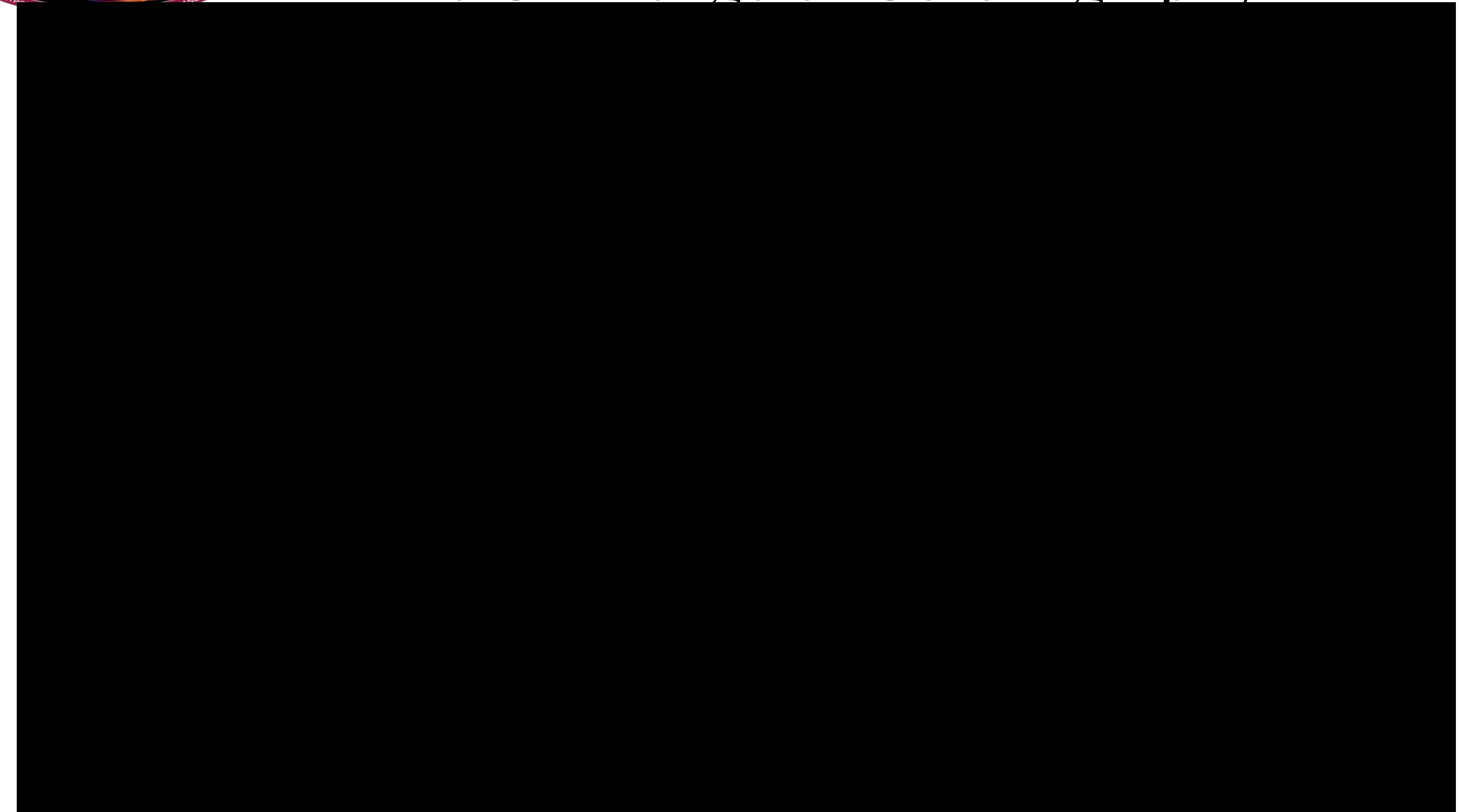
A Firefly and a Spotlight

Seeing an exoplanet around a star is like trying to see a firefly near a spotlight in Los Angeles… when you are in Washington, DC!

Credit: S Gaudi

Seeing an Earth-like exoplanet in the habitable zone around a Sun-like star is like trying to see a firefly near ONE THOUSAND spotlights in Los Angeles… when you are in Washington DC!

The Challenge of Coronagraphy



Coronagraphy- Powers of 10

Contrast Ratio (planet light to star light)

10^{-5} – 10^{-6}1 part in 100,000 to 1,000,000

What we can get from coronagraphs like GPI now and in the near future

Better than 10^{-8} 1 part in 100,000,000

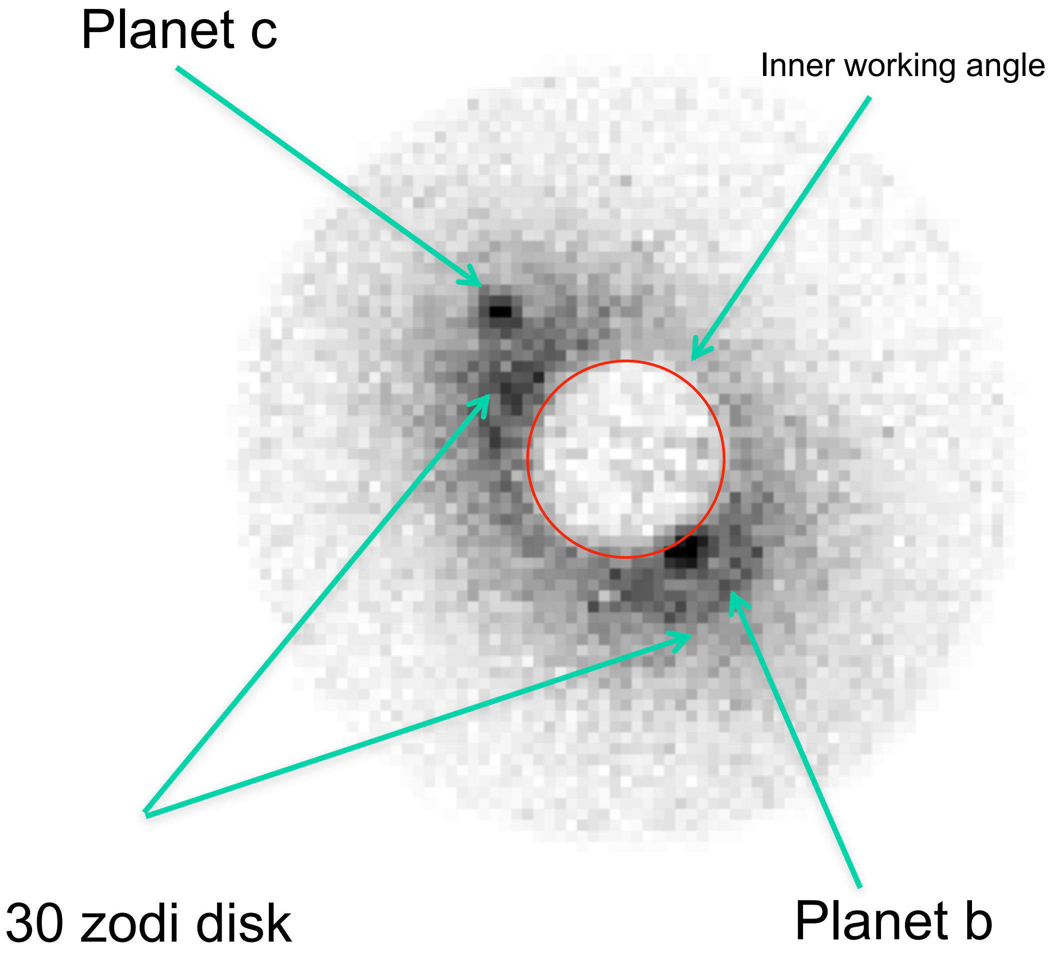
What we have demonstrated in a lab for WFIRST

10^{-9} 1 part in 1,000,000,000

What WFIRST's coronagraph is being designed to achieve

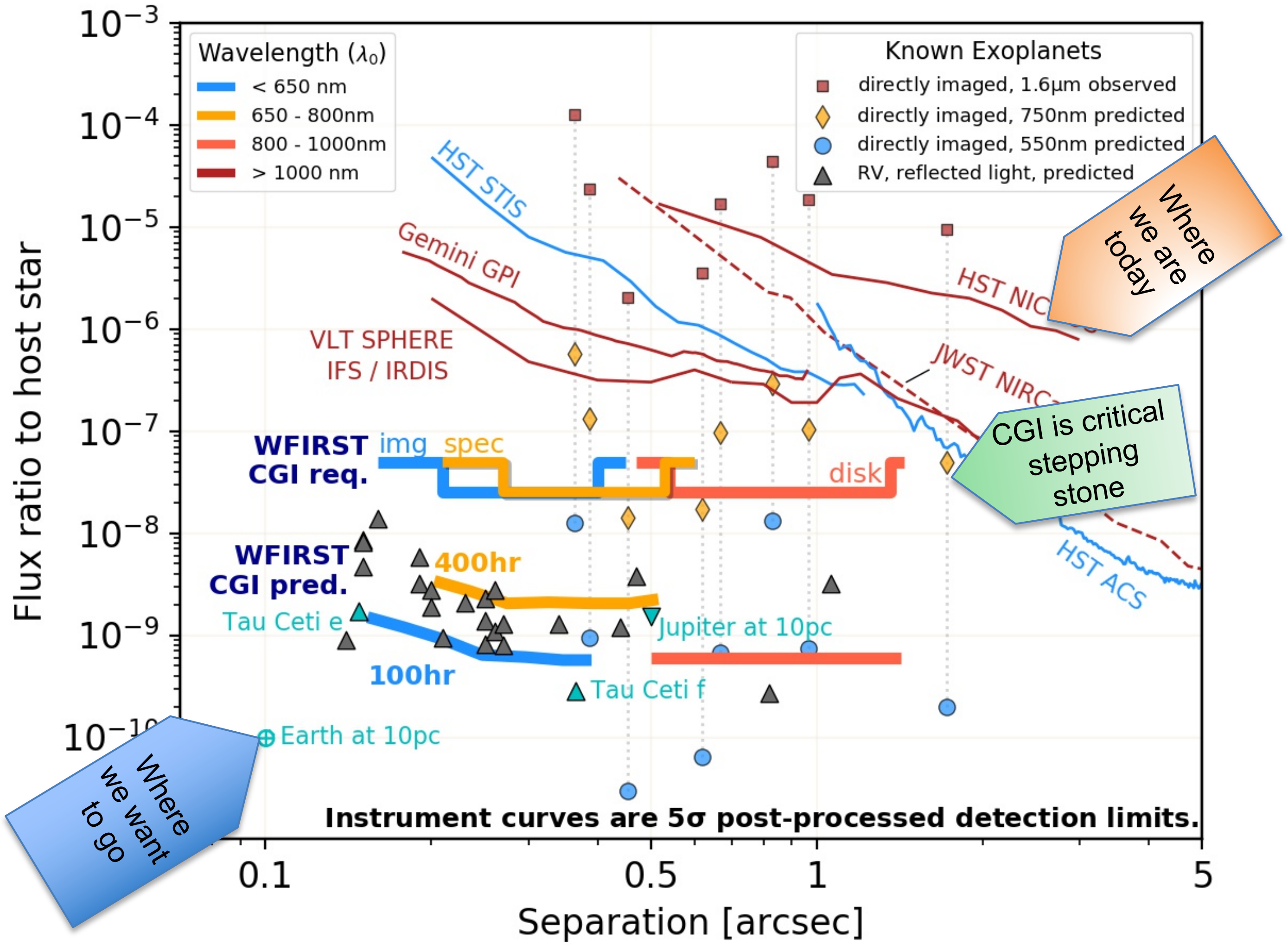
10^{-10} 1 part in 10,000,000,000

What we need to see another Earth (with a afuture mission like HabEx or LUVOIR)

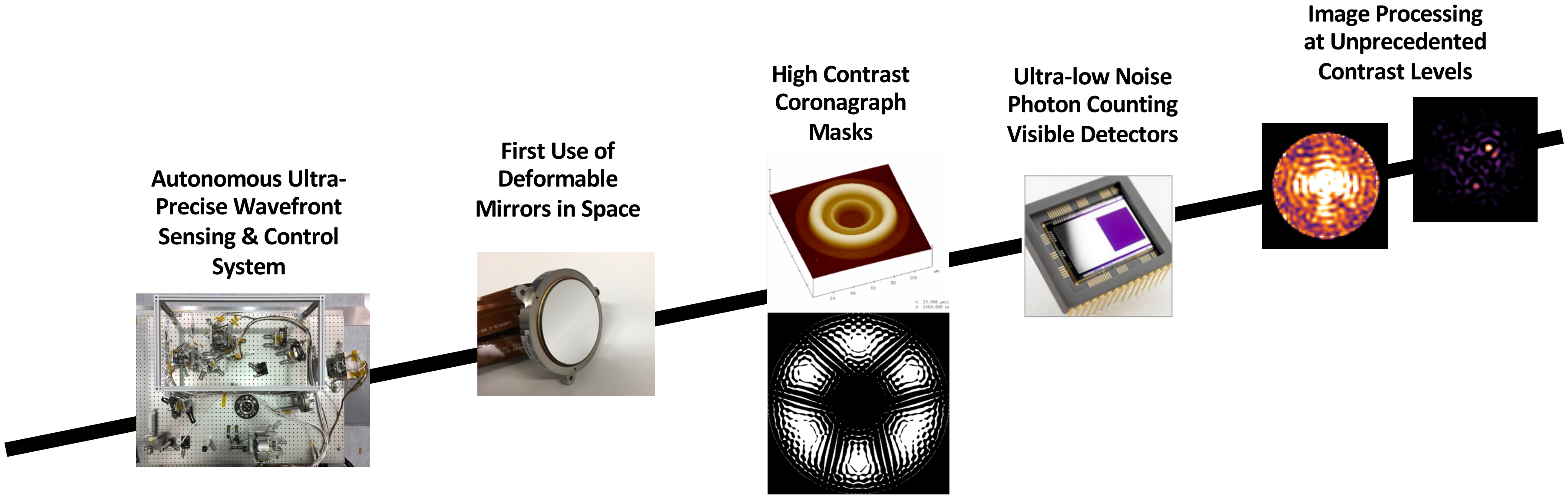


CGI is a Pathfinder for Direct Imaging and Spectroscopy of Earth-like Exoplanets

- CGI projected capabilities represent a 1000 fold compared to current capabilities
  - Enabled by active control of optical wavefront errors and pointing
- Dozens of planets within reach of characterization
- exoEarths in Habitable zone further x10-100 improvement in contrast and x2 in spatial resolution
- CGI is a major stepping stone that will obtain optical spectra of mature exoJupiters



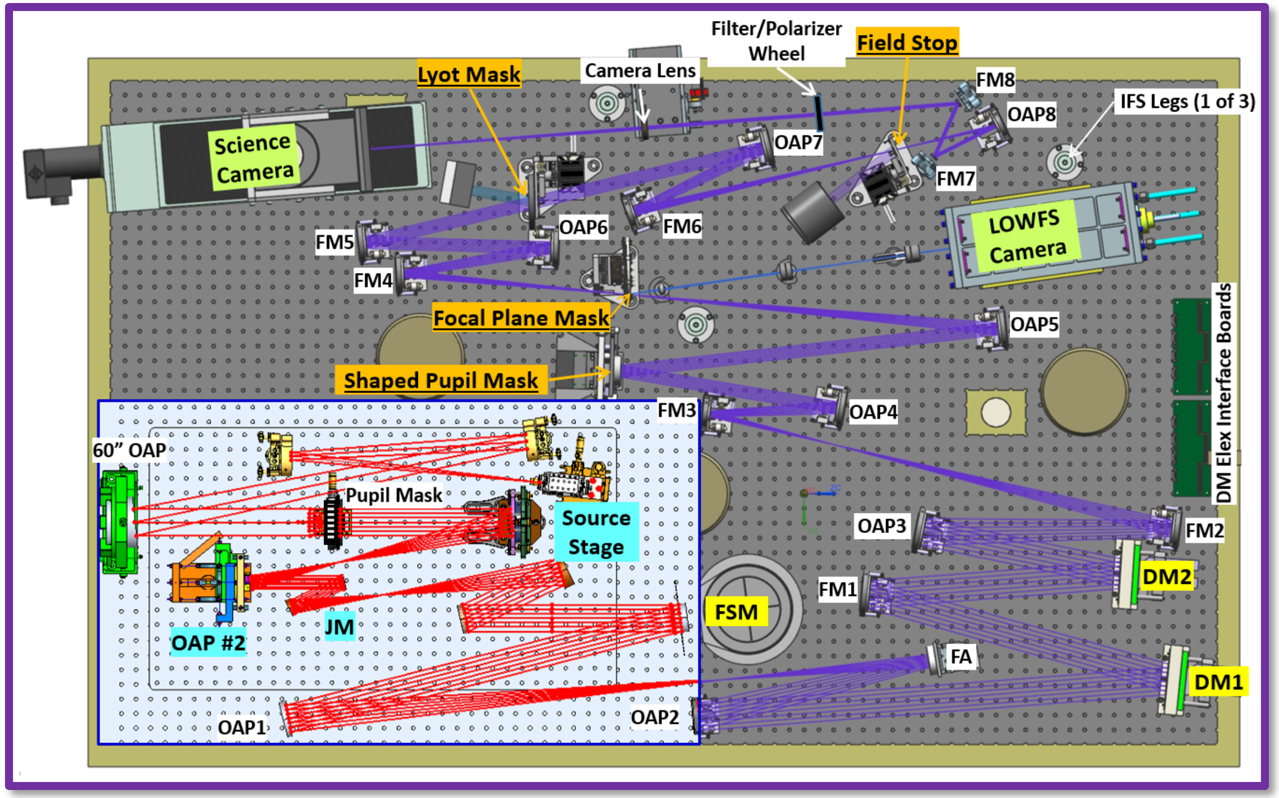
CGI Tech Demonstrations Along the Beam Path



- CGI will premiere in space many key technologies required for the characterization of rocky planets in the Habitable Zone, significantly reducing the risk and cost of future possible missions such as HabEx and LUVOIR

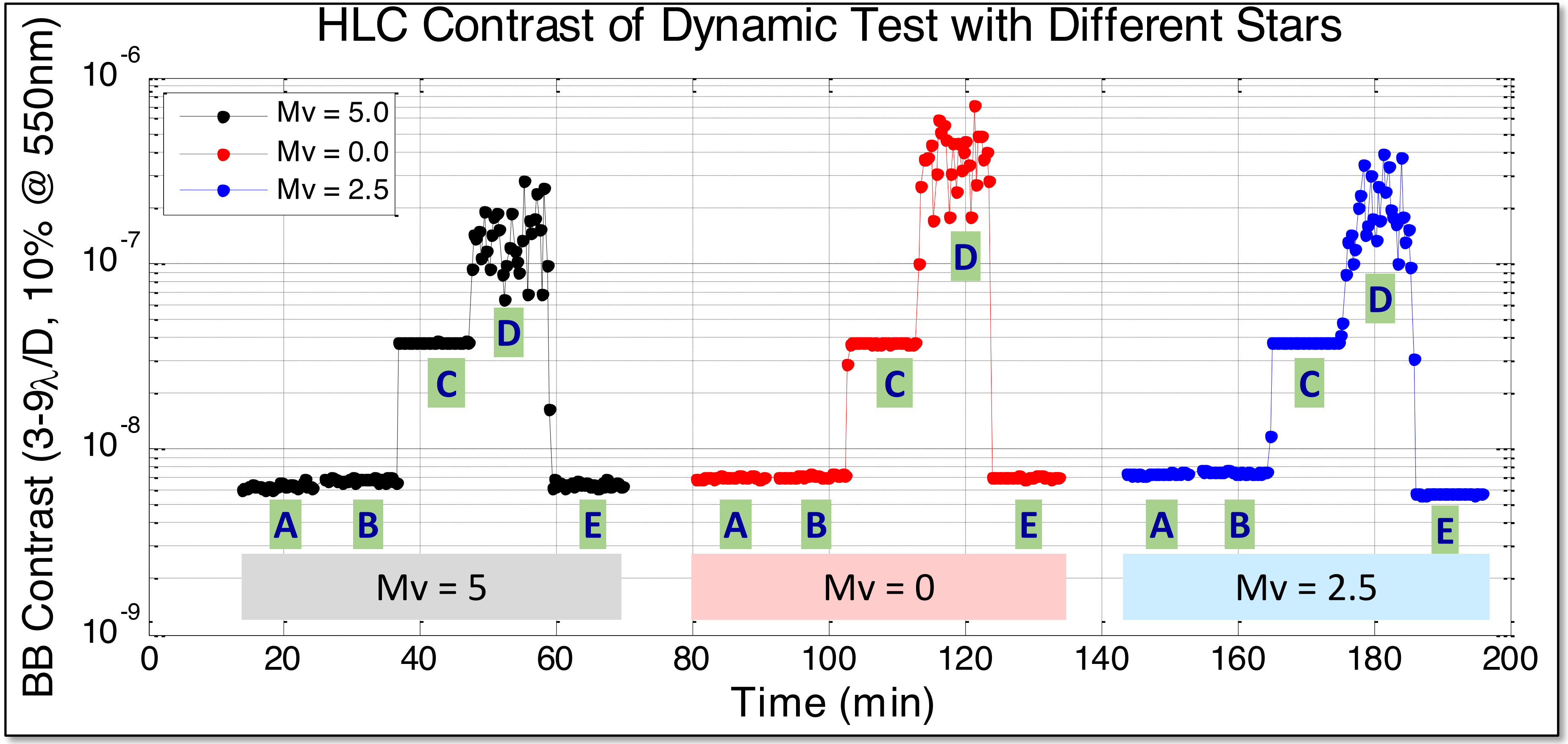
- CGI is a direct & necessary predecessor to these missions, and is a *crucial* step in the exploration of Sun-like planetary systems

WFIRST CGI LOWFS/C Overview



- LOWFS/C subsystem measures and controls line-of-sight (LoS) drift and jitter as well as the thermally induced low order wavefront drift.
- Uses rejected starlight from occulter
- LOWFS is a differential image wavefront sensor referenced to star light suppression wavefront control (HOWFS/C): it maintains wavefront established for high contrast

LOWFS/C LoS Dynamic Test with Different Stellar Magnitudes



BB-Broad Band

FB- FeedBack (control drift)

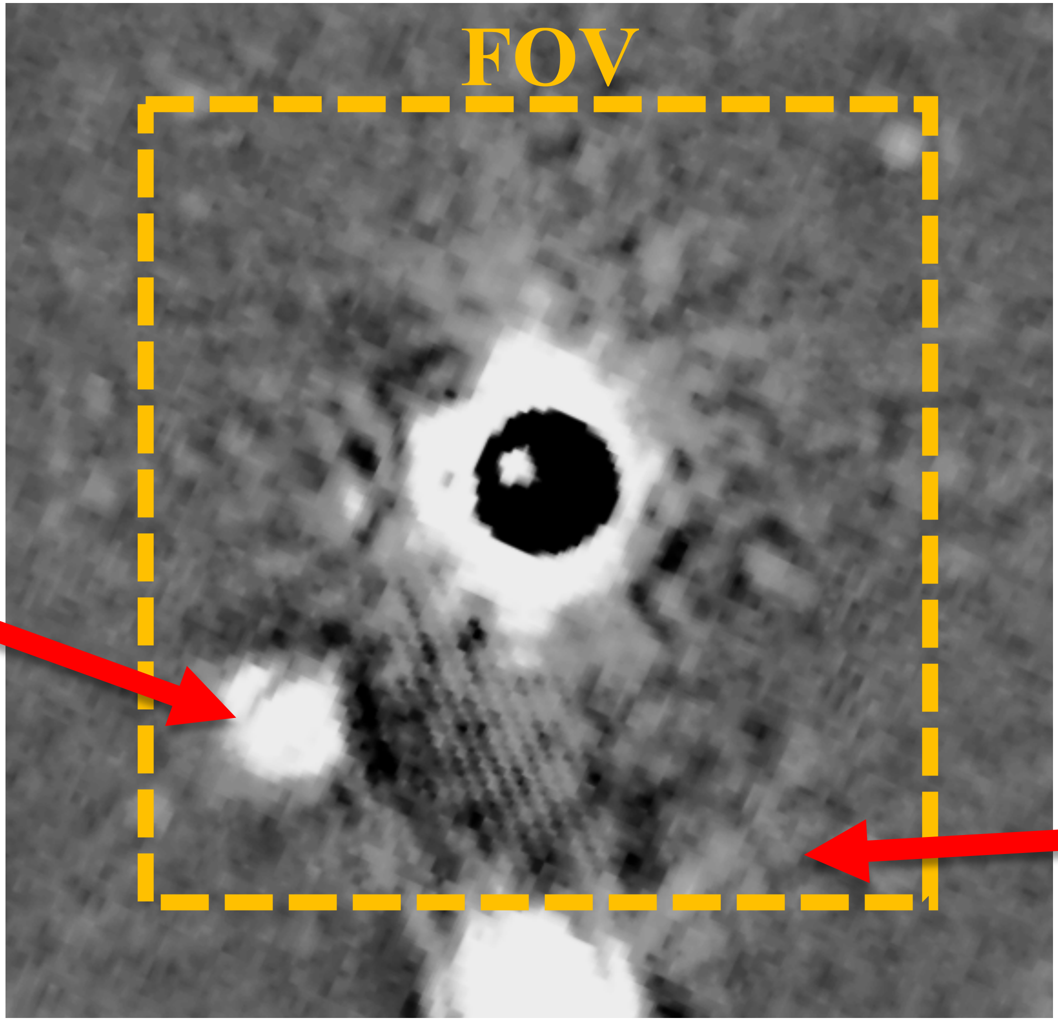
FF- Feed Forward (control jitter, esp. from reaction wheel)

Sequences with each stellar magnitude (Mv = 5.0, Mv = 0.0, Mv = 2.5):

A. FB (drift) on & FF (jitter) on with lab environment
B. FB on & FF on with induced dynamics (ACS + RWA jitter at 600rpm)
C. FB on & FF off with JM induced dynamics (ACS + RWA jitter at 600rpm)
D. FB off & FF off with JM induced dynamics (ACS + RWA jitter at 600rpm)
E. FB on & FF on with lab environment (same as A)

Jet Propulsion Laboratory
California Institute of Technology

Background stars can contaminate CGI images



Interloper
False positives

Glint star
Scattered light.
Extra noise /
obscure planet.

Several high-value CGI targets have non-negligible probability of contamination but can be effectively screened by high-contrast pre-imaging

CGI target location in 2026

Interlopers

Glint stars

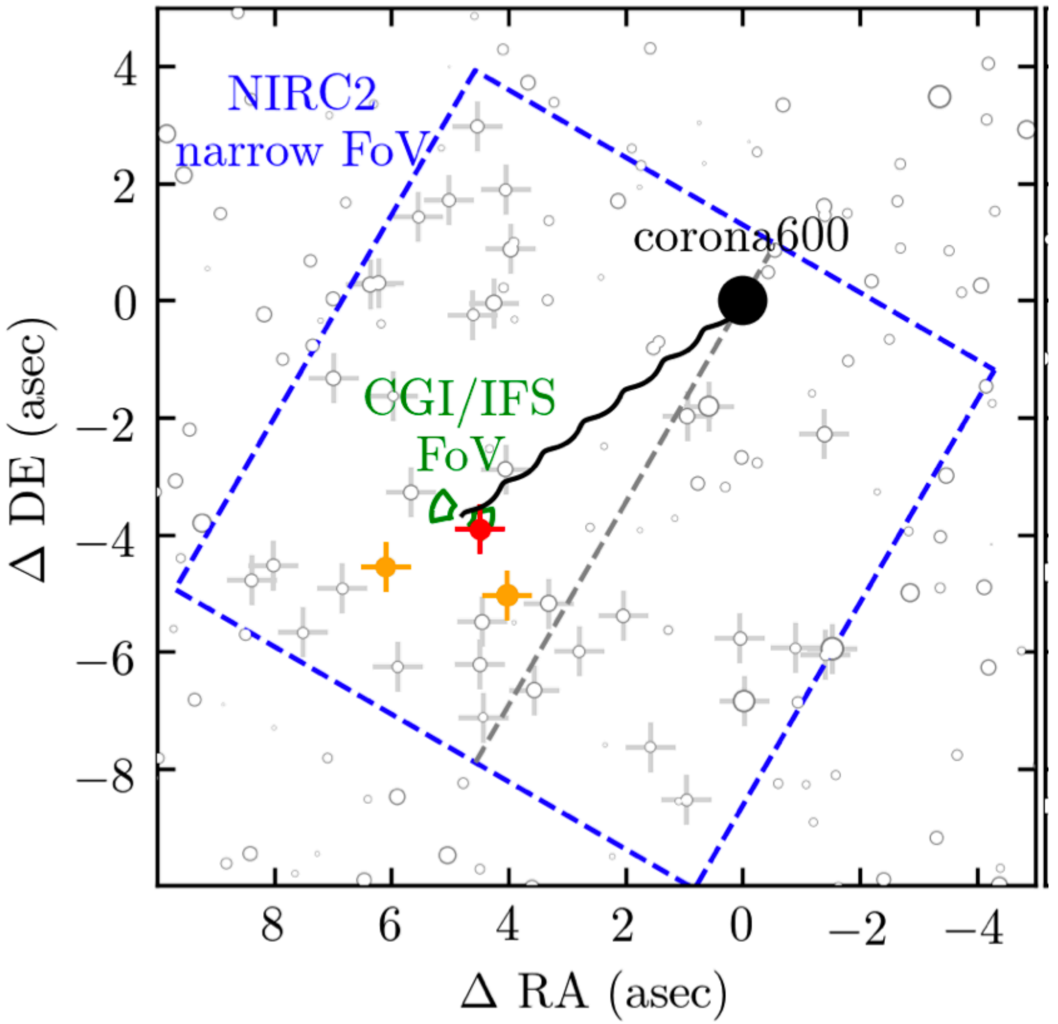
Background stars that don't affect CGI.

CGI target location today

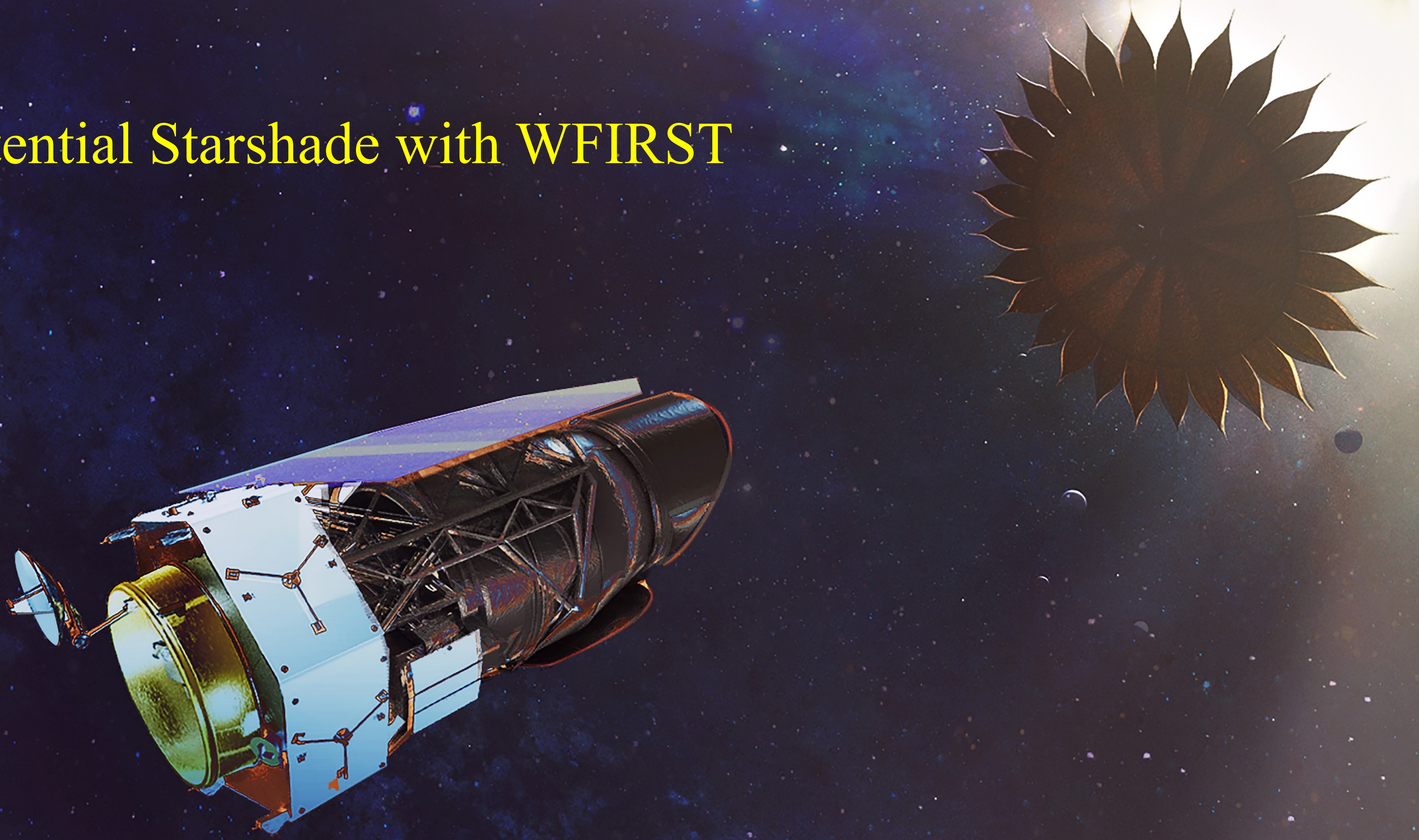
Keck NIRC2 FOV (+ = detectable by NIRC2)

Bailey et al have begun putting in NASA Keck proposals to pre screen CGI targets

Credit: Rob De Rosa

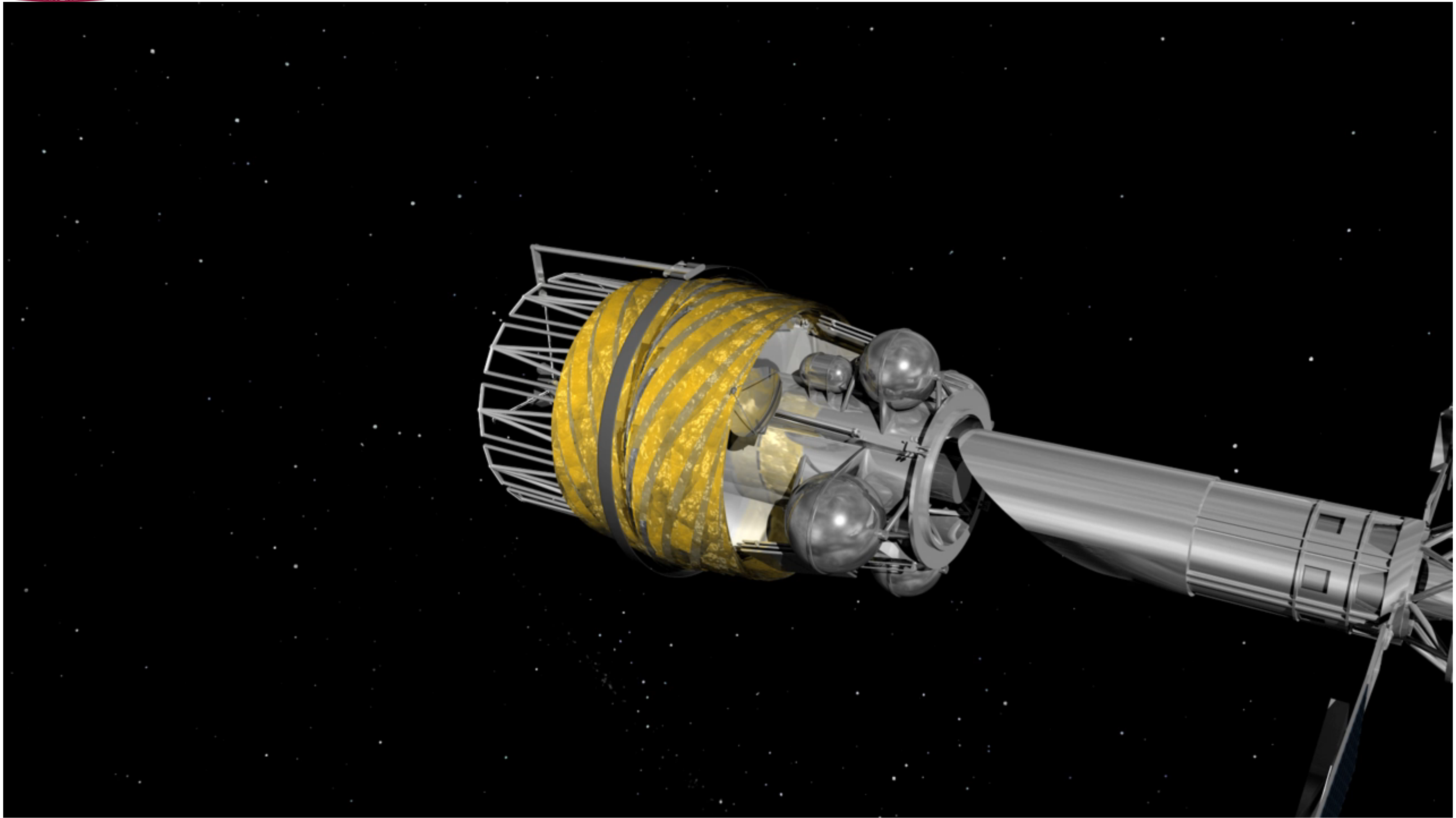


Potential Starshade with WFIRST

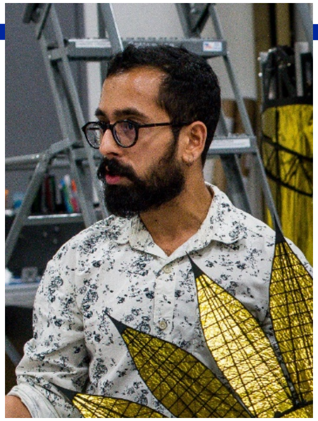


Credit: (Joby Harris, NASA JPL)

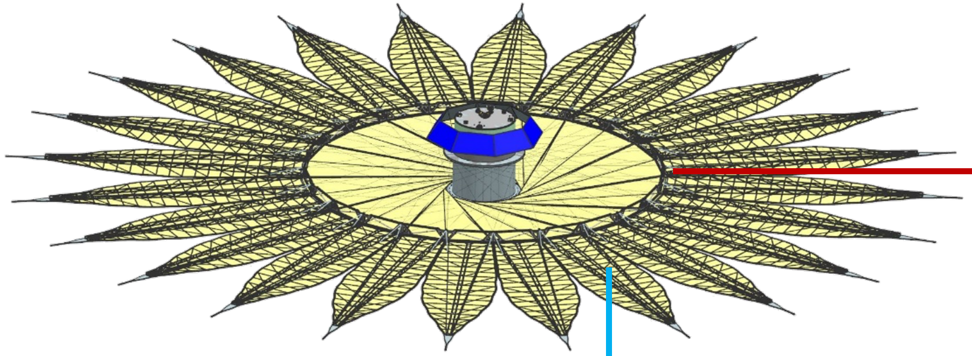
Starshade

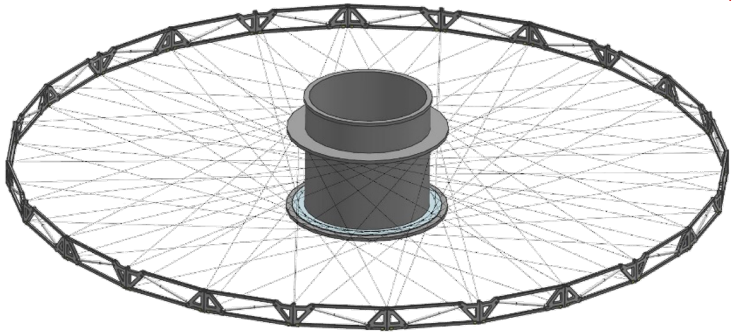


Starshade at JPL

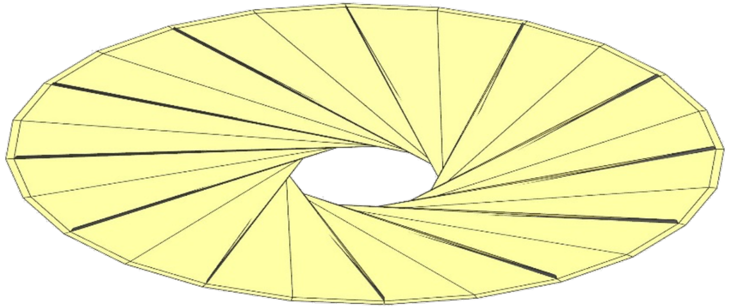


Wrapped architecture splits performance challenges between subsystems that can be verified early by themselves



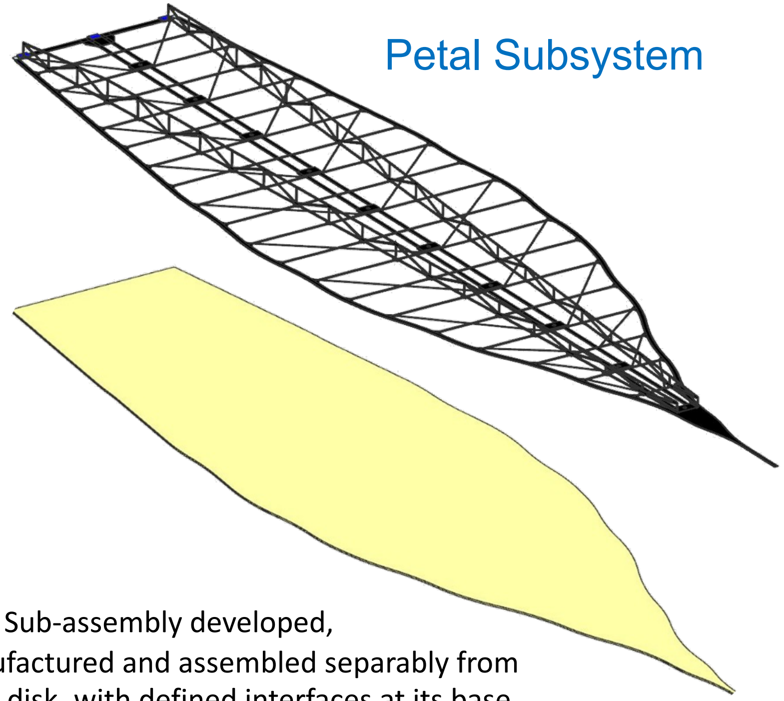


Truss + spokes + hub constitute separable structure w/defined interfaces to petal

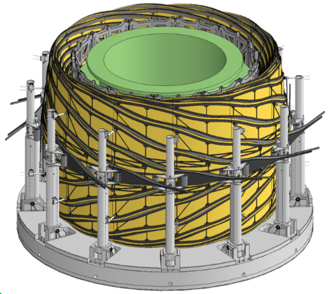


Inner Disk Subsystem

Petal Subsystem



Petal Sub-assembly developed, manufactured and assembled separably from inner disk, with defined interfaces at its base



Petal Launch Restraint & Unfurl Subsystem (PLUS)

PLUS controls petal deployment & defines petal L/R interfaces (jettisoned after launch)

Project Status

- ➢ System Requirements Review / Mission Definition Review held February 27 – March 1
  - Do we have the right requirements? / Does the mission design meet those requirements?
- ➢ Key Decision Point -B completed May 22, 2018
  - **WFIRST now in Phase B!** Allows for beginning of major work with contracts
  - Integral Field Channel descoped – 4/27/2018 (foreign partner unable to commit)

- ➢ White House FY2019 budget request proposed termination of WFIRST to fund other priorities
- ➢ Direction from HQ is to proceed while Congress deliberates
  - *Congress fully funded in FY2018; Committee bills recommend funding for WFIRST in FY2019*

- ➢ Notional schedule (subject to continued appropriations):
  - Preliminary Design Review: late 2019
  - Critical Design Review: mid 2021
  - **Launch: 3rd quarter 2025**

WFIRST Will Provide Critical Exoplanet Data and Pave the Way for a Direct-Imaging Mission

FINDING: A microlensing survey would complement the statistical surveys of exoplanets begun by transits and radial velocities by searching for planets with separations of greater than one AU (including free-floating planets) and planets with masses greater than that of Earth. A wide-field, near-infrared (NIR), space-based mission is needed to provide a similar sample size of planets as found by Kepler.

FINDING: A number of activities, including precursor and concurrent observations using ground- and space-based facilities, would optimize the scientific yield of the WFIRST microlensing survey.

FINDING: Flying a capable coronagraph on WFIRST will provide significant risk reduction and technological advancement for future coronagraph missions. The greatest value compared to ground testing will come from observations and analysis of actual exoplanets, and in a flexible architecture that will allow testing of newly developed algorithms and methods.

FINDING: The WFIRST-Coronagraph Instrument (CGI) at current capabilities will carry out important measurements of extrasolar zodiacal dust around nearby stars at greater sensitivity than any other current or near-term facility.

RECOMMENDATION: NASA should launch WFIRST to conduct its microlensing survey of distant planets and to demonstrate the technique of coronagraphic spectroscopy on exoplanet targets.

From National Academy of Science Exoplanet Science Strategy Briefing, Sept 2018

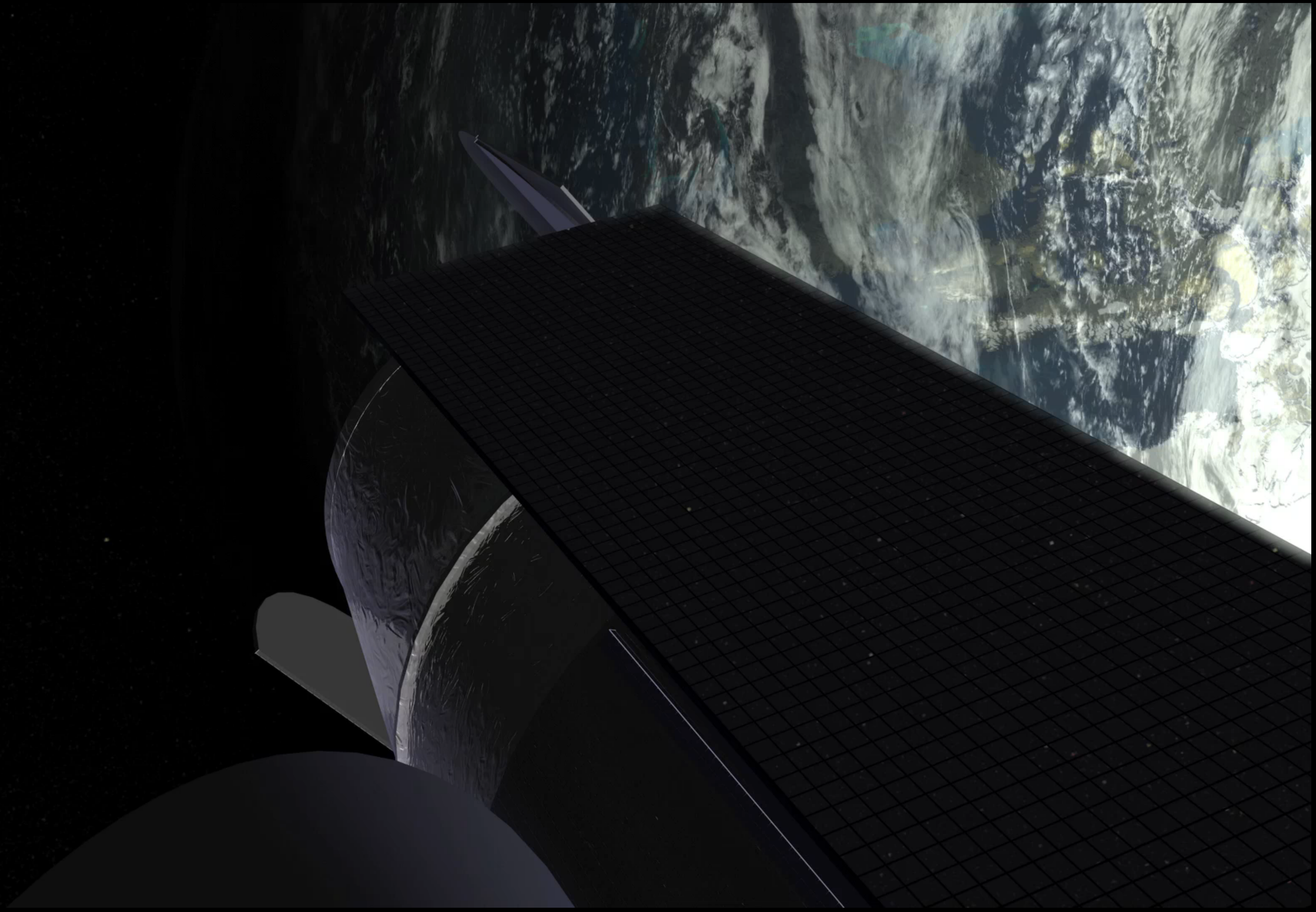
Opportunities with WFIRST

- 2020 Decadal Survey will consider a separate Starshade mission to fly with WFIRST
- 25% General Observer (GO) in 5 year prime mission
- ~100% GO in extended mission
- All prime survey science teams will be competed in ~2021
- All data released immediately- no proprietary period
- CGI available via a Participating Scientists Program
- Baseline mission includes contributions from ESA, France (CNES), Germany (DLR), Japan (JAXA, NAOJ)

The BIG Questions

- What is the Universe made of ?

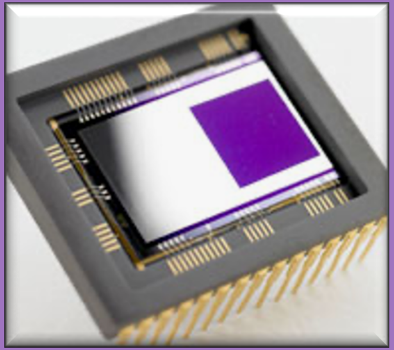
- Are we alone?



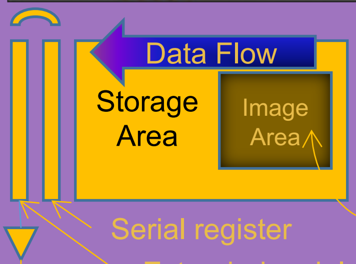
Additional Slides

EMCCDs- High Speed Readout, Zero Noise

e2v L3 Technology



- New technology from e2v enables high QE CCD imaging and **zero read noise** photon counting.
- A **Low Light Level (L3) extended serial register** operating at elevated voltage (~50V) amplifies signals well above the level of the read noise.



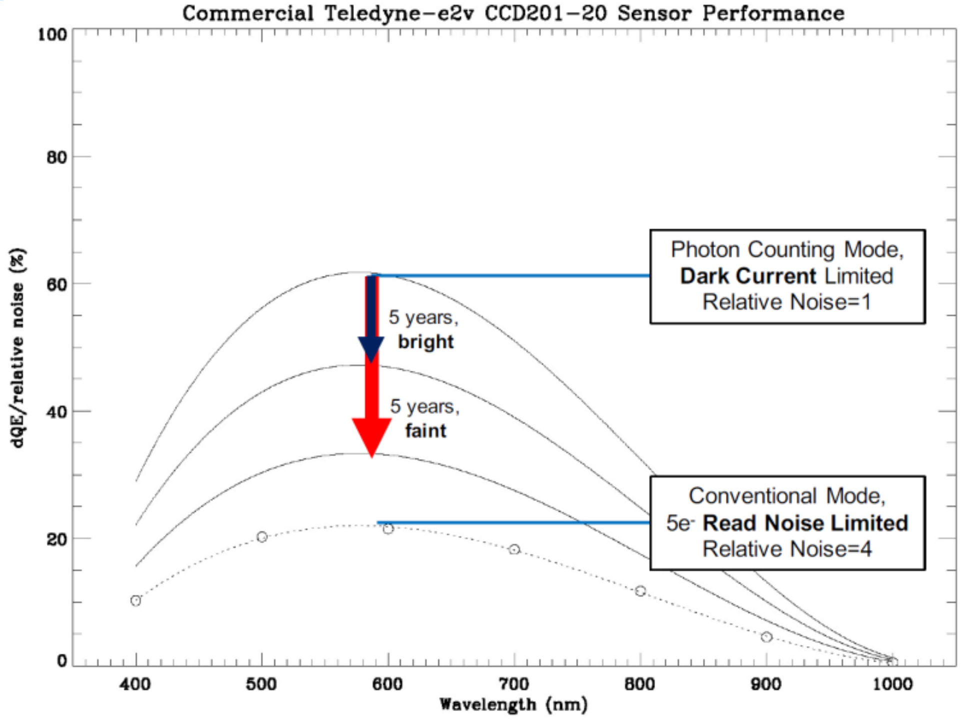
L3 functional diagram

Serial register

Photon input

Extended serial register (50V)

Amplified data is sent to a photon counting discriminator, eliminating read noise.



JPL is working on mitigation for radiation damage:

- Narrowing intrapixel pathways for electrons
- Creating an overflow buffer for cosmic ray induced e-
- Lower noise amplifier

DE SURVEY COMPLEMENTARITY AT A GLANCE

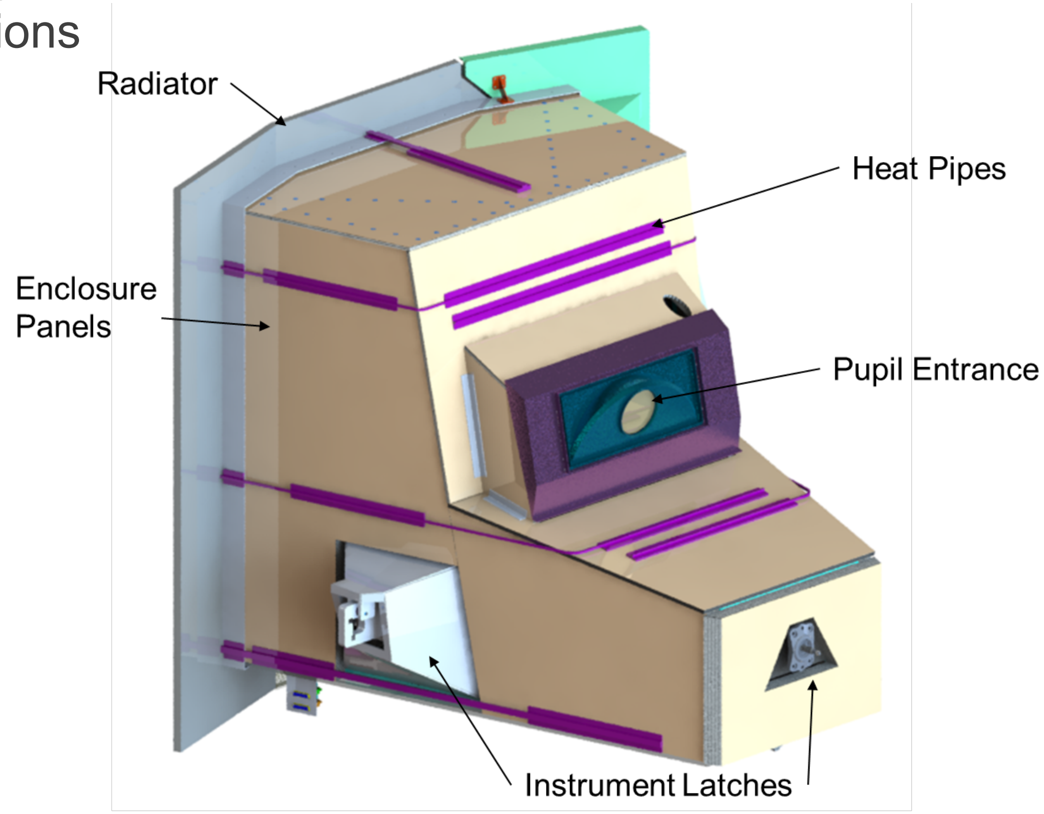
STAGE IV	LSST	WFIRST	Euclid	DESI
Start, duration	2022, 10 yr	~2025, 5 (-10) yr	2021, 6 yr	2019, 5 yr
Area (sq. deg.)	20,000 (S)	2,000 (S)	15,000 (N+S)	14,000 (N)
FOV (sq. deg.)	10	0.281	0.53	7.9
Diameter (m.)	6.7	2.4	1.3	4
Photometric Survey	6 bands (u,g,r,i,z,y)	6 bands (Z,Y,J,H,F,184,W149)	4 bands (VIS,Y,J,H)	
Photometric Galaxies (w/ shapes) (#/arcmin^2)	~30 in 6 bands (ugrizy)	~68 in 4 bands (YJHF184)	~30-35, in 1 band (VIS)	
SN1a	10^4-10^5/yr z=0-0.7 photometric	2700 z=0.1-1.5 IFC spectroscopy		
Spectroscopic Survey		Grism R=550-800 1-2 μm	Grism R=250 1.1-2 μm	Fibers R=4000 0.36-0.98 μm
Spectroscopic Galaxies		ELGs z=0.5-1.8 (Ha/ ~20M) z=0.9-2.8 (OIII/ ~2M)	ELGs, z~0.7-2.1 (20M)	LRGs+ELGs z~0.6-1.7 (20-30M) QSOs/Lya 1.9<z<4 (1M)

Partnerships

JAXA	Coordinated, contemporaneous ground-based observations on Subaru Ground station for telemetry and tracking Polarization optics for the CGI Microlensing data from the MOA project
DLR	Precision mechanisms for the CGI
ESA	Star trackers, possibly other S/C components EMCCD detectors for the CGI Ground station for telemetry and tracking
CNES	Superpolished optics for the CGI Grism data processing Cosmology simulations

Ball Aerospace is partnering with NASA by providing the WFI optical mechanical assembly for WFIRST

- WFI optical mechanical assembly provides the stable structure and thermal environment that enables the wide field, high quality observations of the WFIRST primary instrument
- NASA is responsible for:
  - Focal plane & focal plane electronics
  - GRISM
  - Latches
  - Calibration
  - Ultimate WFI performance
- Ball is responsible for:
  - Enclosure and optical bench
  - Thermal Components
  - Alignment Compensation Mechanism (ACM)
  - Element Wheel Assembly (EWA)
  - Relative Calibration System (RCS)
  - Avionics
  - Assembly, Integration, & Test (AI&T)

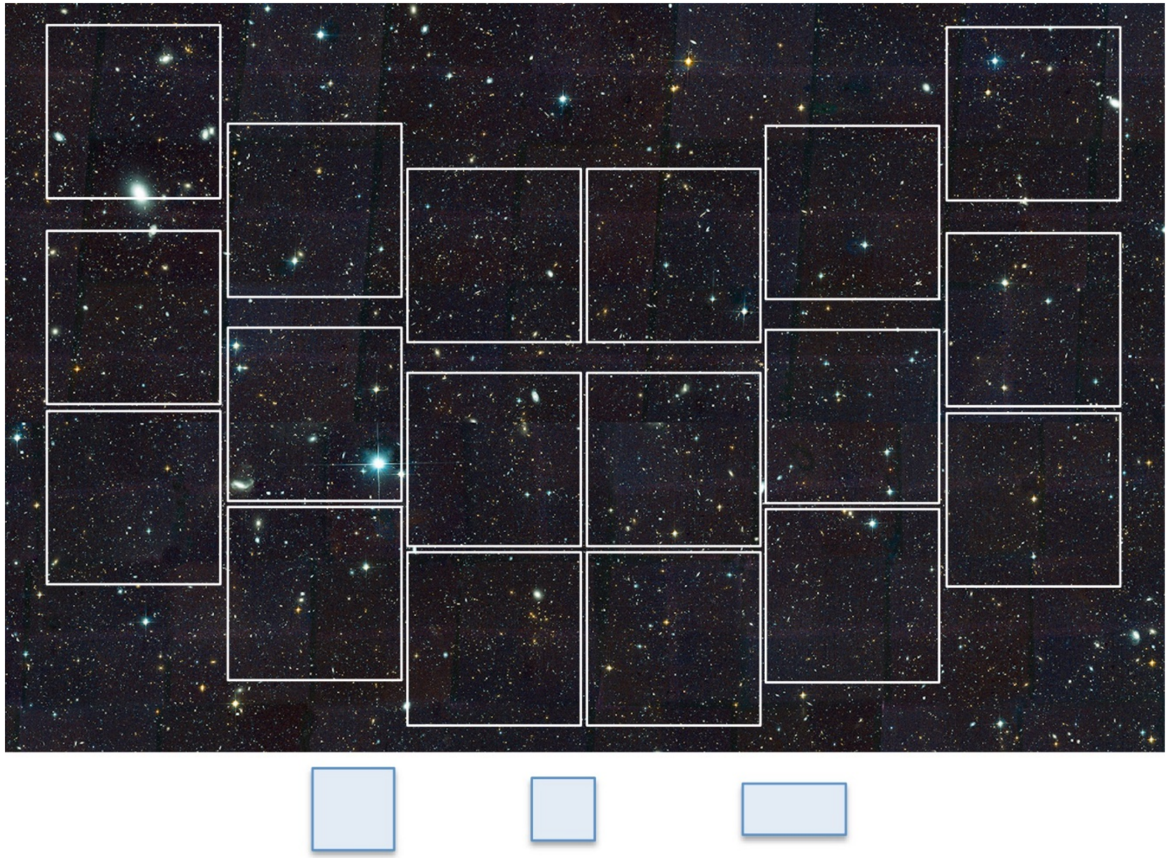


SMD/APMC Direction

- Mission technical baseline unchanged, except:
  - Integral Field Channel descoped – 4/27/2018
    - CSA budget constraints
- Phase A-E cost remains at $3.2B (50% CL)
  - APD to provide "optimal" funding profile
- Notional schedule:
  - PDR: late 2019
  - CDR: mid 2021
  - **Launch: 3rd quarter 2025**

Wide-Field Instrument

WFIRST Field of View

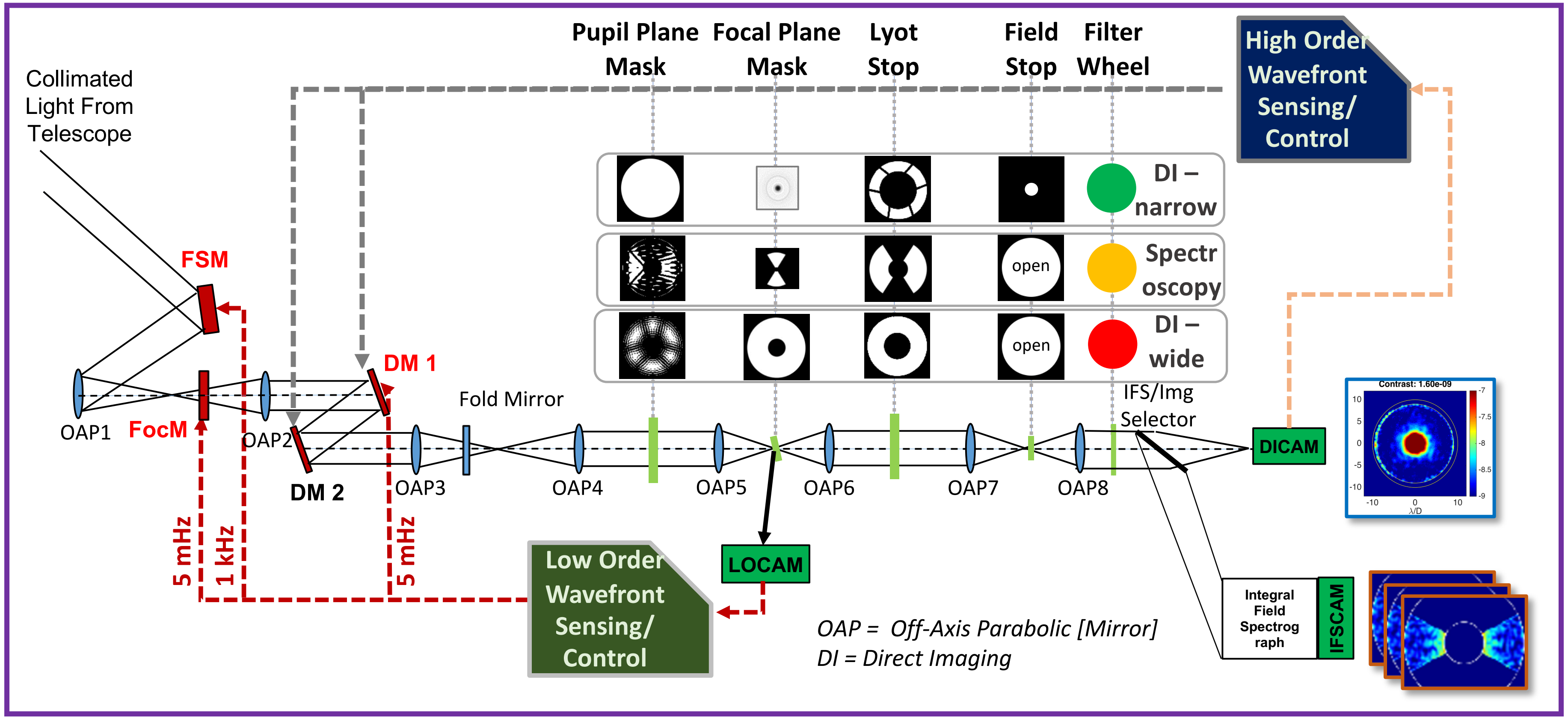


HST/ACS HST/WFC3 JWST/NIRCAM

Diffraction-limited imaging
0.28 square degree FoV
0.11" pixels
R~4 filters spanning 0.48-2.0 μm
Sensitivity: 27.8 H(AB) @5σ in 1hr

Slitless grism:
1.0-1.93 μm
R: 435-865

WFIRST CGI LOWFS/C Overview

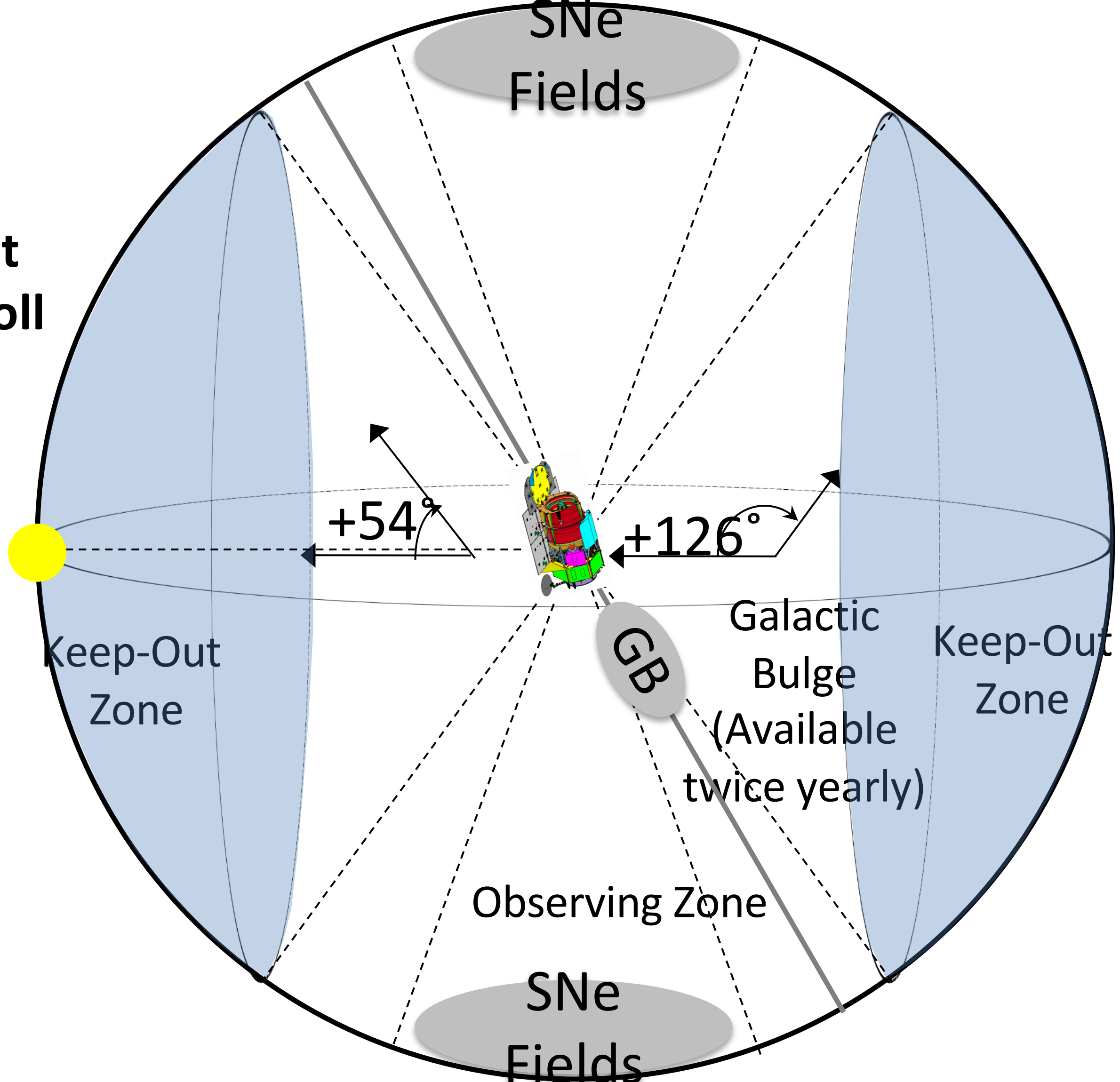


- LOWFS/C subsystem measures and controls line-of-sight (LoS) drift and jitter as well as the thermally induced low order wavefront drift.
- Uses rejected starlight from occulter which reduces non-common path error
- LOWFS sensor is a Zernike wavefront sensor (ZWFS).
- LOWFS is a differential image wavefront sensor referenced to star light suppression wavefront control (HOWFS/C): it maintains wavefront established for high contrast

Field of Regard (FOR)

Observing Zone:
- **54°-126° off Sun Line**
- **360° about Sun Line**
- **±15° about line of sight (LOS) off max power roll angle**

HLS/GO/Coronagraph observations can be optimized within the full Observing Zone



SNe fixed fields ±20° off of the ecliptic poles, located in continuous viewing zone

Earth/Moon LOS avoidance angles are a minor sporadic constraint

Microlensing can observe inertially fixed fields in the Galactic Bulge (GB) for 72 days twice a year

WIDE-FIELD INFRARED SURVEY TELESCOPE

WFIRST

DARK ENERGY • EXOPLANETS • ASTROPHYSICS

Observatory Expanded View

Observatory = Spacecraft + Payload